Quadrupedal Locomotion Based in a Purely Reflex Controller

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Keywords: Quadruped Locomotion, Reflexes, Sensory Information.

Abstract: Quadruped locomotion in irregular and unknown terrains is still a problem to solve. The concept of reflexes is used in this work to contribute for the continuous search of answers about this theme. Biological researches show that spinal reflexes are crucial for a successful locomotion in the most varied terrains, so robotics investigation in this area could be a great advance in the robot's locomotion.
In this work, we present a sensory driven reflex controller, capable of generating locomotion in a quadruped compliant robot. This controller is totally dependent on sensory information, so the robot's movements are the result of the robot interactions with the environment. Results show that the proposed controller is capable of generating movements in a flat terrain and is resilient to unexpected perturbations such as a small ramp.

1 INTRODUCTION

It is generally accepted that locomotion in animals is generated at the spinal cord level by a combination of central pattern generators (CPG) and reflexes(Geyer and Herr, 2010),(Kimura et al., 2007). In order to achieve adaptation to irregular terrains, the robot must have "motor intelligence"(Cruse et al., 1998), and adapts its moves according to unexpected situations. Animals show an efficient solution to the locomotion problem and so appear as an interesting alternative to mimic in robotics.

Locomotion generation is largely dependent on reflexes: animals react to specific stimulus by generating particular movements. In fact, Charles S. Sherrington (Burke, 2007), defended that rhythms could be the result of a chain of reflexes triggered and governed by external sensorial events, producing the final rhythmic locomotor activity. Even though locomotion is a centrally generated process, sensory feedback plays an important role in the adaptation and correction of legged locomotion (see (Pearson, 2004) for an important review).

It has been shown that the CPG and locomotion generation is highly integrated and dependent on feedback pathways. For instance, it has been demonstrated (Rossignol et al., 2006) that sensory events can adjust the duration of the rhythmic activity, stimulation of sensory afferents can elicit locomotion and sensory removal deteriorates locomotor abilities, such as precise foot placement. Moreover, the generation of locomotion is adapted according to sensory information, and this occurs at different levels.

All these aspects evidence the fact that locomotion generation is much more complex than a simple feedforward process of muscle activations. In this paper, we further tackle this problematic and we propose a purely sensory-driven reflex controller inspired on biological studies performed in animals, mainly cats. The proposed controller is only based on the interactions of the robot with the environment, therefore sensory information is a crucial element in the movement of the robot. The goal is to accomplish a parsimonious controller, resorting to the minimum number of reflexes to produce a successful quadruped walking behavior. The final controller should be able to generate a sequence of motor actions triggered by external sensory events, accomplishing stepping motor behaviors. Moreover, the quadruped robot should be able of avoiding small external disturbances of the ground such as small ramps. It is assumed that the final trajectories are not previously known, and should result from the interplay between the motor actions and the sensory information. The walking behavior should be an emergent realization of motor actions reflecting the general rules as encoded in the reflexes, and not a result from strict tracking of a predefined desired behavior.

Locomotion has also been achieved by the application of simple sensory driven reflexes rules, both in

Ferreira C., Matos V., P. Santos C. and Ijspeert A..
Quadrupedal Locomotion Based in a Purely Reflex Controller.
DOI: 10.5220/0005062403240331
In *Proceedings of the 11th International Conference on Informatics in Control, Automation and Robotics* (ICINCO-2014), pages 324-331
ISBN: 978-989-758-039-0

simulations and in robotic platforms (Geyer and Herr, 2010; Cruse et al., 1998). Several works comprising CPG and reflexes have been made in the last twenty years. In the earliest studies with reflexes Ekeberg and Wadden implemented a neuronal model of a single leg, that combines properties of mechanical and neuronal systems(Wadden and Ekeberg, 1998). Cruse *et al.* projected a bio-inspired controller of a hexapod robot that generates locomotion based on sensory events(Cruse et al., 1998). Kimura *et al.* presented various quadruped robots, Patrush, Tekken, Tekken2, capable of walk dinamically on irregular terrain, using nervous system models based on CPG and reflexes(Kimura et al., 2000),(Fukuoka et al., 2003),(Kimura et al., 2007). Based on Ekeberg work, Maufroy *et al.* presented a simulation model of the two hind legs of a quadruped robot, which also has a controller based on CPG and sensory events(Maufroy et al., 2008). An implementation on the Oncilla robot is also described in (Ajallooeian et al., 2013a; Ajallooeian et al., 2013b). Finally, Geyer and Herr presented a muscular model of human locomotion only controlled by muscle reflexes, exploiting principles of legged mechanics(Geyer and Herr, 2010).

Most of the presented works on reflex based locomotion are implemented in simulation, using models of musculoskeletal fore and hind legs, with the solution producing muscle activations, or the torques to be applied at the joints calculated from the musculoskeletal models. Considering only reflexes, the work by H. Cruse and the work by Wörgötter are applied to rotational controlled DOFs in robots. In the case of H. Cruse the generator outputs the joint velocities for the hexapod robot, and in Wörgötter's work, the locomotion generator outputs motor voltages for the biped robot. However, in all these works three sensory events are used to trigger locomotor actions (reflex based walking) or regulate the rhythm activity of the CPGs. In common is the use of the angle of the hip joint, regulating the timing of the stance and swing phases. It is also used the signals indicating ground contact from foot sensors, or even leg load, used to inhibit the transition from the stance phase to the swing phase.

The proposed controller is based on these works. The proposed reflex system controls a quadruped robot with position controlled hips and retractable, passive compliant knees. Some of these reflexes express motor activities as a continuous activity depending on sensory information, e.g. ground contact promoting/reinforcing the stance phase of the step. It is therefore assumed that joint velocity is the best abstraction for the output of the system based on the reflexes. Reflexes reflect a rate of change dependent on sensory information, producing motor actions while a determinate sensory condition is maintained, or mimic positive feedback mechanisms found in the motor control of animals. This assumption accepts that joint positions change while necessary, and sensory events determine the final output trajectory.

Simulations were produced in the simulated Oncilla quadruped robot with position controlled hips and retractable, passive compliant knees. Results show that the projected controller fulfills the required goals. Further, the robot becomes quite resilient to external disturbances, such as small ramps.

2 REFLEX-BASED QUADRUPED LOCOMOTION

We define some bio-inspired conditions for the success of quadruped locomotion:

(a) The hip position is key factor in the transition between the stance and swing phases (Grillner and Rossignol, 1978),(McVea et al., 2005),(Pearson, 2008);

(b) The stimulation of the footpad promotes the stance phase (Duysens and Pearson, 1976);

(c) The unloading of the leg is a necessary condition for swing phase initiation (Hiebert et al., 1994),(Hiebert et al., 1995),(Pearson, 2008);

3 REFLEX NETWORK

The proposed sensory-driven controller, depicted in figure 1, includes four distinct modules: sensory information , sensor neurons, external inputs and phase neurons, as described in the following.

It is considered that one step cycle is divided into four motor actions: Lift-off - reduction of the leg length by flexing the knee; Swing - bring the leg forward by acting on the hip; Touchdown - having the leg in the rostral (to the front) position, increase the leg length to support the foot on the ground, by extending the knee; Stance - propulsion of the robot by acting on the hip.

These motor actions are not mutually exclusive in time, for example, the swing action could be executed just after lift-off has started.

The position controlled joints track the position as integrated from the reflex system output in joint velocity, $\dot{\theta}_i$, $i = h, k$ for hip and knee joints, respectively.

For the hip joint: a) By specifying a positive velocity for the hip joint, the leg produces the motion of

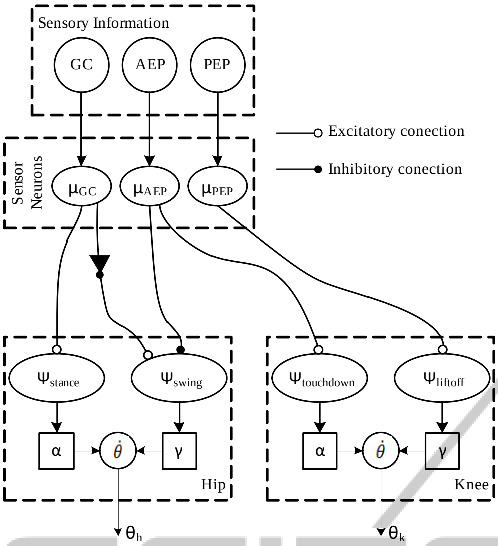

Figure 1: Proposed Controller for a robot's leg.

propulsion, reflecting the hip action in the **stance**; b) A negative velocity for the hip joint transfers the leg to the front, reflecting what happens in the **swing**.

For the Knee joint: a) A positive velocity in the knee flexes the leg and decreases the leg length, achieving **lift-off**; b) And a negative velocity in the knee releases the spring, extending the leg, achieving **touchdown.**

These motor actions are implemented by assigning fixed rates of change, activated by discrete neuron activations from a reflexive network dependent on sensory information.

Despite the joint output generator being in the form of velocity the desired output is the joint position. The velocity joint output is directly dependent on the neuronal activity of the phase neurons, as follows:

$$\dot{\theta}_{\mathrm{h}} = \alpha_{\mathrm{h}}\Psi_{\mathrm{stance}} - \gamma_{\mathrm{h}}\Psi_{\mathrm{swing}} \quad (1)$$

$$\begin{aligned}\dot{\theta}_{\mathrm{k}} &= -(\alpha_{\mathrm{k}}\Psi_{\mathrm{touchdown}} - \gamma_{\mathrm{k}}\Psi_{\mathrm{liftoff}}) \\ &+ g_{\mathrm{lim}}(\theta_{\mathrm{k}} - \Theta_{\mathrm{k,max}})\exp^{-\frac{(\theta_{\mathrm{k}}-\Theta_{\mathrm{k,max}})^2}{2\sigma^2}} \quad (2) \\ &+ g_{\mathrm{lim}}(\theta_{\mathrm{k}} - \Theta_{\mathrm{k,min}})\exp^{-\frac{(\theta_{\mathrm{k}}-\Theta_{\mathrm{k,min}})^2}{2\sigma^2}}\end{aligned}$$

where Ψ are the phase neuron activations of the described actions ($\Psi \in [0,1]$), and α and γ are the fixed rates of change for hip and knee joints. To limit the range of activity on the knee, due to its limited range of action, two joint limiting terms are included. Parameters g_{lim} and σ define the strength and width of the repeller, respectively. The values of $\Theta_{\mathrm{k,max}}$ and $\Theta_{\mathrm{k,min}}$ are the maximum and minimum knee joint limits, respectively.

3.1 Sensory Inputs

The sensory inputs to the reflex network translate sensory events based on the leg's sensory information: the touch sensor of foot-pad to detect ground contact; joint position to be able to detect the anterior extreme position (AEP) and posterior extreme position (PEP).

These sensory events are detected through the sensor neurons, μ_{GC}, μ_{AEP}, μ_{PEP}, implemented as logistic functions, activated ($= 1$) when the sensory values cross a defined threshold: μ_{GC} becomes active when the touch sensor of the foot-pad exceeds a threshold; μ_{AEP} becomes active if hip exceeds the AEP angle; and μ_{PEP} becomes active if hip exceeds the PEP angle. These neurons are implemented with sigmoid functions, allowing the sensor neurons to become active when the sensory value exceeds a certain threshold:

$$\mu_{\mathrm{AEP}} = \frac{1}{1+\exp^{-b(\theta_{\mathrm{h}}-\Theta_{\mathrm{AEP}})}} \quad (3)$$

$$\mu_{\mathrm{PEP}} = \frac{1}{1+\exp^{b(\theta_{\mathrm{h}}-\Theta_{\mathrm{PEP}})}} \quad (4)$$

$$\mu_{\mathrm{GC}} = \frac{1}{1+\exp^{b(F_{\mathrm{threshold}}-F_{\mathrm{touch}})}} \quad (5)$$

where Θ_{AEP}, Θ_{PEP} and $F_{\mathrm{threshold}}$ are the specified threshold values; θ_h is the measured hip joint angle and F_{touch} is the sensor reading.

3.2 Phase Neurons

A single leg is controlled by four neurons, which determine the activation of the four motor actions of the robot step cycle. Two motor actions are assigned to the hip joint, each governed by one neuron, **swing** and **stance**. The other two motor actions, **lift-off** and **touch-down** are assigned to the knee joint. The velocity joint output is directly dependent on the neuronal activity of these phase neurons.

The reflex network is based on a non-spiking neuron model. These neurons are simple leaky integrators and have a output value between 0 and 1. The excitatory (ξ_{+j}) and inhibitory (ξ_{-j}) synaptic inputs are calculated from first-order differential equations and were adapted from (Wadden and Ekeberg, 1998), as follows:

$$\dot{\xi}_{+j} = \frac{1}{\tau}\left(\sum_{i\in\Upsilon_+}\mu_i w_i - \xi_{+j}\right) \quad (6)$$

$$\dot{\xi}_{-j} = \frac{1}{\tau}\left(\sum_{i\in\Upsilon_-}\mu_i w_i - \xi_{-j}\right) \quad (7)$$

where j represents the phase neuron (stance, swing, touchdown, liftoff), τ is the time constant,Υ_+ and Υ_- are the sets of excitatory and inhibitory synapses, w_i

is the strength of synapse: $w \in [0,1]$ and u_i is the output value from the corresponding presynaptic neuron. The neuron activation of the phase neurons was also adapted from (Wadden and Ekeberg, 1998), as follows:

$$\Psi_j = \begin{cases} 1 - \exp((\Theta - \xi_{+j})\Gamma) - \xi_{-j} & \text{, if positive} \\ 0 & \text{, otherwise} \end{cases} \quad (8)$$

The output of the neuron model reflects a mean firing rate, between 0 and 1, and is characterized by its time constant, the gain Γ and the activation threshold Θ.

3.3 Network Behavior

Based on the description of the biological rules and the four sensory events, the following behaviors are encoded in the reflex network as excitatory and inhibitory connections (*i* stands for one leg):

- Hip reaching AEP elicits the touchdown action on the knee, exciting the touchdown neuron, extending the knee: $\Upsilon_{+,\text{touchdown},i} \supset \{(\mu_{\text{AEP},i})\}$ and $w_{\text{AEP},\text{touchdown},i} = 1$.
- Hip reaching AEP inhibits the continuation of hip protraction: $\Upsilon_{-,\text{swing},i} \supset \{(\mu_{\text{AEP},i})\}$ and $w_{\text{AEP},\text{swing},i} = 1$.
- Hip reaching PEP elicits liftoff, making the knee flex: $\Upsilon_{+,\text{liftoff},i} \supset \{(\mu_{\text{PEP},i})\}$ and $w_{\text{PEP},\text{liftoff},i} = 1$.
- Ground contact elicits and reinforces the stance, propelling the robot forward: $\Upsilon_{+,\text{stance},i} \supset \{(\mu_{\text{GC},i})\}$ and $w_{\text{GC},\text{stance},i} = 1$.
- Lack of ground contact excites the swing neuron: $\Upsilon_{+,\text{swing},i} \supset \{(1 - \mu_{\text{GC},i})\}$ and $w_{\text{GC},\text{swing},i} = 1$.

Note the relationships between the excitations and inhibitions of the neurons and the used biological rules: ground contact activates μ_{GC}, exciting the stance neuron and promoting stance phase - rule (b); hip reaching the anterior extreme position activates μ_{AEP}, inhibiting the swing neuron and exciting the touchdown neuron - rule (a); Lack of ground contact de-activates μ_{GC}, exciting swing neuron and promoting swing phase - rule (c); hip reaching the posterior extreme position activates μ_{PEP}, exciting the liftoff neuron - rule (a);

3.4 Contralateral and Ipsilateral Coordination

The simple reflex network depicted in figure 1 is enough to produce stepping motions in a single leg.

Although independent leg reflex networks produce alternated stepping in a girdle, the addition of an inhibitory contralateral connection imposes strict alternation of step phases, preventing the execution of simultaneous swing motor action on contralateral legs.

Ipsilateral leg coordination is necessary to prevent the execution of the swing motor action in ipsilateral legs, as in a pace gait, and impose some phase relationship in ipsilateral legs to achieve walk or trot gaits. Ipsilateral coordination (fig. 2) can be achieved by applying an inhibitory connection when a strict alternation of ipsilateral legs is desired: Lack of ground contact in the ipsilateral leg (*o*), inhibits the initiation of the lift-off (in leg *i*): $\Upsilon_{-,\text{liftoff},i} \supset \{(1 - \mu_{\text{GC},o})\}$ and $w_{\text{GC},\text{liftoff},o} = 1$.

The inhibitory contralateral connection (fig. 3) comes from the contralateral ground contact sensory neuron, to the lift-off motor action in the knee: Lack of ground contact in the contralateral leg (*j*), inhibits the initiation of the lift-off (in leg *i*): $\Upsilon_{-,\text{liftoff},i} \supset \{(1 - \mu_{\text{GC},j})\}$ and $w_{\text{GC},\text{liftoff},j} = 1$.

4 SIMULATIONS

In this section we describe some Webots simulations made on the compliant quadruped robot Oncilla. The Oncilla is a small quadruped robot, with pantograph, three-segment leg design, providing passive compliant behavior to the cable driven retractable knees. It has 12 degrees-of-freedom, three on each leg: hip-swing, hip-flap and knee. The robot has compliant knees and the hip joints are position controlled. Pertaining videos are available at http://asbg.dei.uminho.pt/user/1.

The reflex network is parameterized empirically and based on other works (Wadden and Ekeberg, 1998; Maufroy et al., 2008; Ekeberg and Pearson, 2005).

The experiments are divided into two experimental setups. The first setup is intended to accomplish the full quadruped walking on straight, flat terrain. The second one is intended to verify the ability of the robot to deal with perturbations, namely to climb up a ramp with a maximum inclination of 8.9 degrees. As far as startup conditions are concerned, the joint positions are established such that the contralateral limbs are at the AEP and PEP positions, and initial neuron activities are set to the respective step phase. Table 1 shows the set of parameters used for these experiments, setting the sensory thresholds necessary for the the sensory neurons and the joint output parameters.

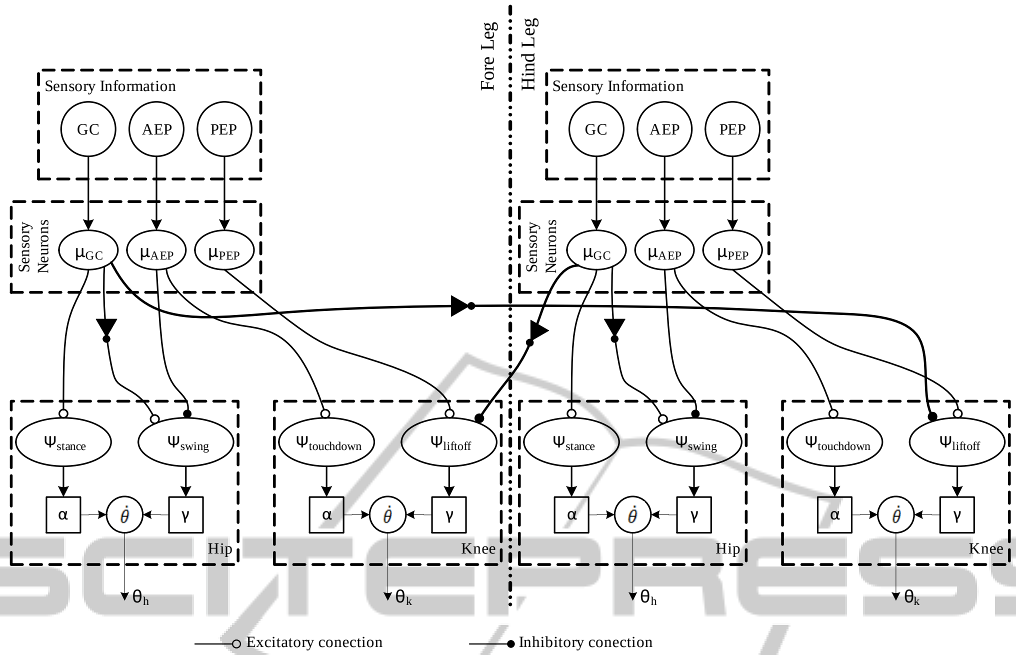

Figure 2: Proposed Controller for ipsilateral leg coordination. The lack of ground contact inhibits the ipsilateral liftoff phase on the knee.

Table 1: Sensory Thresholds and Joint output Parameters.

Parameters	Fore legs	Hind Legs
Θ_{AEP}	12	10
Θ_{PEP}	7	5
$F_{\mathrm{threshold}}$	1	1
α_h	50	50
γ_h	400	400
α_k	300	300
γ_k	500	500

Simulations show that the robot is able to move in a flat terrain and to go up a ramp, with a controller only based on the robot interactions with the environment.

4.1 Flat Terrain Experiment

In this simulation the robot uses both fore and hind girdles, thus accomplishing stepping motions of the legs while propelling and maintaining the robot's balance (fig. 4). First we will focus on how the sensory events trigger the sequence of reflexes which produce the motor actions.

Figures 5 and 6 depict fore left leg's hip and knee joint movement, respectively, the phase neurons, as well as the sequence of activation of the sensory neurons. Initially, the *stance* neuron is active ($\Psi_{\text{stance}} = 1$, dashed blue line in fig. 5) due to the existence of ground contact μ_{GC}, producing a constant propulsive motion in the hip. After the hip angle reaches the PEP value ($\mu_{\text{PEP}} = 1$), the *lift-off* neuron is activated (Ψ_{liftoff}, solid red line in fig. 6), producing a flexion motion of the knee, shortening the leg's length and lifting the foot from the ground. The lack of ground contact ($\mu_{\text{GC}} = 0$) activates the *swing* neuron Ψ_{swing} (solid red line in fig. 5) which produces a flexion motion of the hip, transferring the leg to a rostral position. After reaching the AEP value ($\mu_{\text{AEP}} = 1$), the *swing* neuron (Ψ_{swing}, solid red line in fig. 5) is deactivated halting the motion of the hip, and the touchdown neuron ($\Psi_{\text{touchdown}}$, dashed blue line in fig. 6) becomes active, producing the extension of the knee and the consequent foot placement. Just as the foot regains contact with the ground ($\mu_{GC} = 1$), the *stance* neuron becomes active ($\Psi_{\text{stance}} = 1$, dashed blue line in fig. 5) and produces the propulsive motion of stance. The sequence repeats onwards, producing the stereotyped motions of walking.

Figure 7 presents the obtained stepping sequence. Note that the obtained robot stepping sequence is irregular. In table 2 we present the locomotion characteristics of this experiment: the swing time (T_{sw}), the stance time (T_{st}), the duty factor (β) and the robot velocity.

The obtained motor behavior can be said to resemble a walk, despite the lack of a constant periodic

Table 2: Locomotion Characteristics in Flat (ramp) Terrain.

Characteristics	FL	FR	HL	HR
$T_{sw}(s)$	0.231 (0.231)	0.256 (0.235)	0.123 (0.119)	0.120 (0.124)
$T_{st}(s)$	0.403 (0.380)	0.380 (0.374)	0.488 (0.426)	0.439 (0.434)
β	0.636 (0.622)	0.598 (0.614)	0.799 (0.781)	0.785 (0.778)
Velocity(m.s^{-1})	0.088 (0.079)			

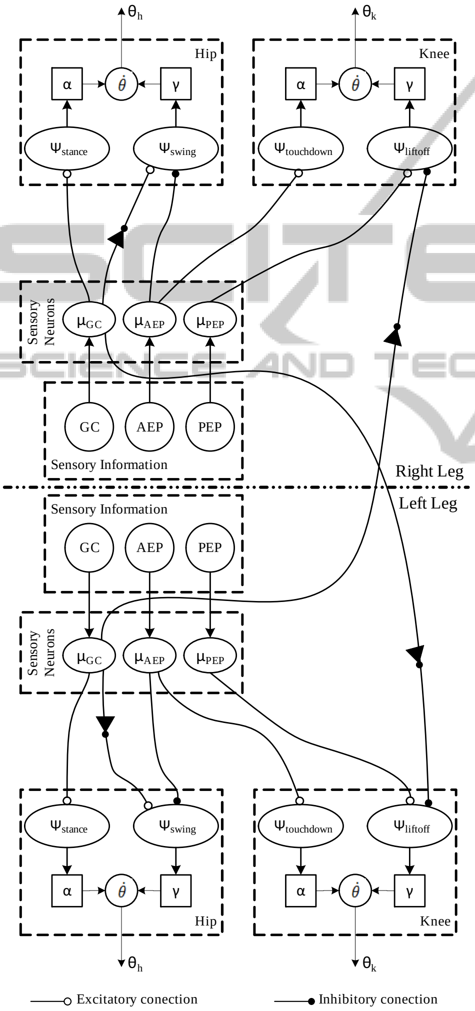

Figure 3: Proposed Controller for contralateral leg coordination. The lack of ground contact inhibits the contralateral liftoff phase on the knee.

pattern. From the stepping sequence it is possible to ascertain that the robot performs a walking behavior which resembles a mix between a trot and a diagonal sequence walk. The stepping sequence also evidences an asymmetry along the sagittal plane, concerning the fore legs. In the fore girdle, there is an asymmetry in duty factor, with one leg having a greater support duration, randomly alternating between the right fore and the left fore. In fig. 7 at around 3 s and at 6 s it is noticeable this asymmetric pattern (red box).

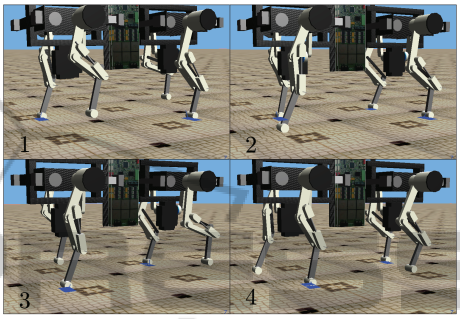

Figure 4: Simulation of quadruped walking using the reflex network.

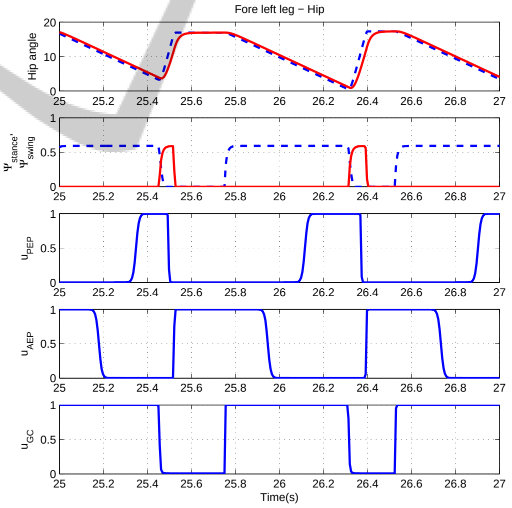

Figure 5: Fore left leg's hip joint movement, swing and stance phase neurons and sensory neurons. For the hip angle, the dashed blue line represents the reference hip value and the red solid line the produced joint angle. For the phase neurons (stance and swing), the dashed blue line represents the stance neuron and the solid red line the swing neuron.

Despite a not ideal stepping sequence pattern, the robot effectively propels itself forward while maintaining an upright posture, without falling over.

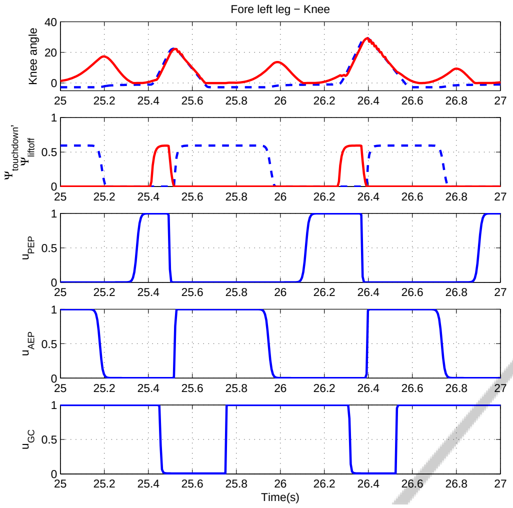

Figure 6: Fore left leg's knee joint movement, touchdown and liftoff phase neurons and sensory neurons. For the knee angle, the dashed blue line represents the reference knee value and the red solid line the produced joint angle. For the phase neurons, the dashed blue line represents the touchdown neuron and the solid red line the liftoff neuron.

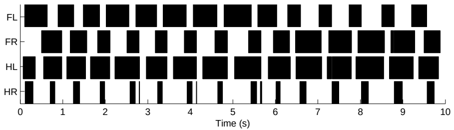

Figure 7: Oncilla stepping sequence pattern in flat terrain.

4.2 Climbing a Ramp

Figure 8 presents the obtained stepping sequence for the climbing ramp scenario, when the robot has to climb a ramp of 8.9 degrees. In table 2 we present the locomotion characteristics of this experiment.

The robot is capable of dealing with ramps even though it does not have specific mechanisms to do so. It goes up with difficulty and the sequence stepping gets worse, but propulsive stepping was produced. This shows up the intrinsic robustness of the controller. The figure 8 shows the robot walking patterns in the ramp and although its irregularity, it is perceptible the walking movement of the robot. Comparing the obtained values in table 2 we can see that the robots velocity decreased in the climbing ramp situation, as expected.

Figure 9 shows the body pitch angle of the robot in the ramp climbing situation.

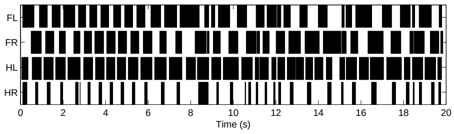

Figure 8: Oncilla stepping sequence pattern on a ramp.

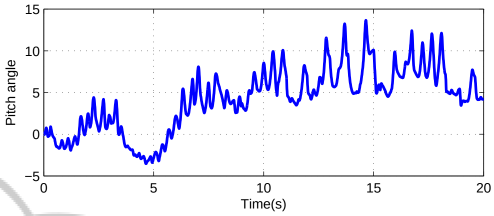

Figure 9: Robot's body pitch angle when going up a ramp.

5 CONCLUSION

In this contribution we present a purely reflex neural controller capable of generate stable locomotion in a quadruped robot. This work is the first step in the development of a bio-inspired controller capable of generating robust locomotion in many types of environments.

Future work includes the implementation of more reflexes to improve the robot locomotion and add noise to the sensory system to test the robot's behavior. We also want to implement a evaluation stability system to validate our experiments and finally add a feed-forward component in order to have a robust controller.

ACKNOWLEDGEMENTS

This work has been supported by FCT – Fundação para a Ciência e Tecnologia within the Project Scope PEst OE/EEI/UI0319/2014.

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