ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Adaptive Locomotion Controller for a Quadruped Robot

Step 1:

Model of sensory feedback in animals during locomotion

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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 study will try to describe the various sensory feedback mechanisms during locomotion.

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 [2]. 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 [6]. 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.

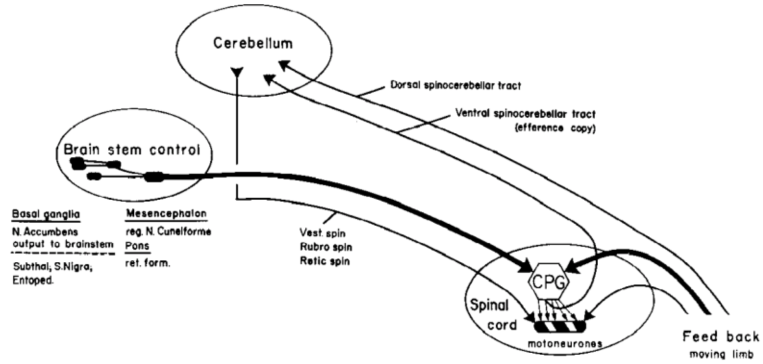

Figure 1: Schematic diagram of the control system for locomotion in vertebrates. Reproduced from [10].

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 [15]. The spinal cord also retrieves information from muscles through special muscles receptors, see 4.1.2 for more information.

The role of alpha and gamma motoneurons is also of big importance in motor control. Stretch of the sensory organ (muscle spindles, see 4.1.2.1) 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 [17].

4 Sensory feedback

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.

4.1.1 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 [8] and recent experiments showed that removing cutaneous inputs from the hindlimbs did not prevent locomotion [11]. 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 [2]. 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 [1]; see 4.2.3 for a further study of this example.

4.1.2 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.

4.1.2.1 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 [16]. 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 [12].

4.1.2.2 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 [12].

4.2 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.

4.2.1 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 [4].

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 [13]. 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 [2].

4.2.2 Stance-to-swing transition

Initiation of the swing phase is a crucial phase of the step cycle. Physiological data[14] 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 [14]. 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 [4].This corresponds to reduction of positive feedback from extensor group Ib afferents at the end of the stance phase. In [9] they 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 crucial for regulating the stance-to-swing transition.

4.2.3 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 [8].

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 we stimulate the foot 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 [8]. Because these stimuli occur during a phase of weight support, the actual limb movement appear less obvious that with perturbations during swing.

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.

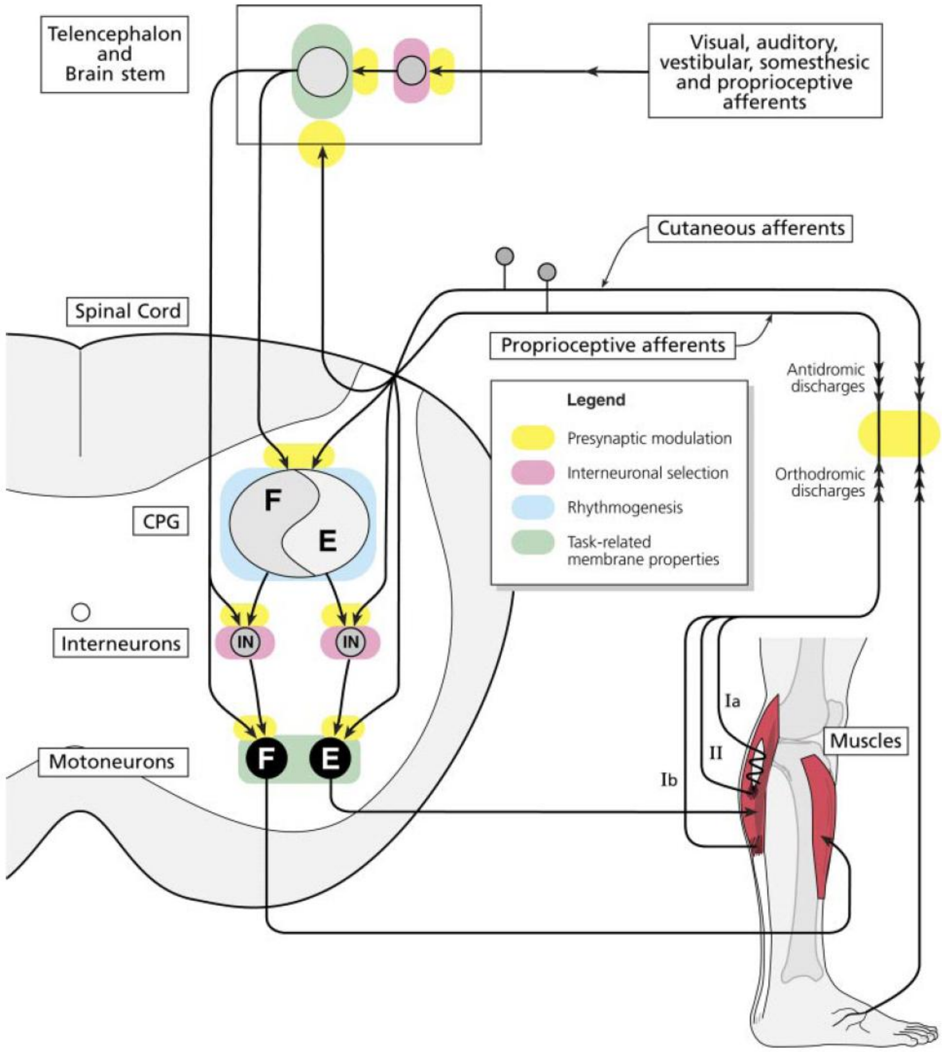

Figure 2: View of the most important sensorimotor interaction sites playing a role during locomotion. Reproduced from [8].

6 References

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