

Control principles for locomotion – looking toward biology

Avis H. Cohen

University of Maryland, Biology Department and Institute for Systems Research, College Park,
MD 20742

Abstract

Presented here is an overview of some principles for control of locomotion that are seen in all animals and which offer ideas for robotic design and control. The intention of the overview is to suggest new ways to think about and to perhaps design legged machines taking inspiration and guidance from biology. Some additional potential features of motor control seen in mammalian species are also presented as further examples of concepts that might prove useful for robotic design.

1. Introduction

The discussion in this paper will focus on universal principles present in virtually all animals studied, vertebrate and invertebrate. Animals using these principles have survived and done well through evolutionary time. We can have some confidence that the principles that cut across such a wide variety of animals have most likely been heavily selected for to help in that survival, and that the principles are important and highly adaptive control strategies. Two less universal principles are also described for potential robotic design, with some discussion of how they are implemented in the biological system and what they might contribute to artificial systems. Examples of how one might implement the control strategies will be presented from robots of colleagues, H. Kimura, University of Electro-Communications, Tokyo, and A. Lewis, Iguana Robotics. The paper will provide further explanation of the principles as well as pointing to additional material including references, and pedagogical lectures made available in PDF format.

2. CPG and muscle activation

2.1 CPG structure and basic motor pattern

Locomotion in animals could be produced by passive mechanics as the limbs impact the environment (for a passive robot cf. Ref. 1). The muscles and tendons of animal limbs have a remarkable ability to store and release energy (cf. Full, this volume), but, passive mechanics would be inadequate for swimming, uphill locomotion or for locomotion on an absorbent substrate such as sand. It is also known that during locomotion a feedforward excitation to the muscles exists that can be independent of sensory feedback and brain input [2, 3] (figure1).

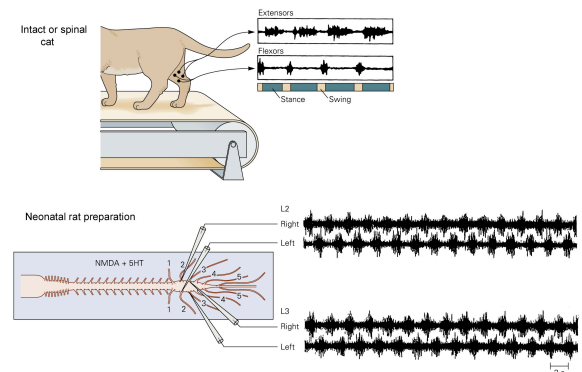


Figure 1: Demonstration of CPG in mammals

Demonstration of the existence of CPG in mammals: Above, the pattern of flexion and extension seen in a cat that is either fully intact or spinalized but with sensory feedback present. Below, a fully isolated spinal cord a neonatal rat is capable of producing a stable alternating pattern of muscle activity similar to that seen during walking. (Adapted from ref 4, data from isolated rat spinal cord from ref 5)

The feedforward muscle activation is generated by a “central pattern generator (CPG)” within the spinal cord. The basic pattern, while not requiring sensory feedback or brain input, does interact with feedback during movement (see below for description of this interaction.)

There is one example of an invertebrate that seems to rely almost entirely on sensory activated reflexes for its locomotion (cf. Cruse presentation), but its walking is so slow that the reflex activation provides perfect ongoing adjustments to environmental conditions.

There is considerable evidence that the spinal CPG of vertebrates is a neural circuit of coupled non-linear oscillators, coordinated by ascending and descending fibers via strong connections. The structure and organization of the spinal CPG is best understood in the lamprey, a fish-like animal that is evolutionarily at the bottom of the vertebrate line. Its spinal cord, while simple, contains all the critical vertebrate components of the nervous system. Furthermore, the outputs of the CPG throughout the vertebrates can be shown to be related to each other by only simple transformations [6]. Thus, the organizational principles found in lamprey are apt to hold for other vertebrates, even those with limbs. In addition to its anatomical simplicity, the lamprey also has the advantage that it lacks any limbs or paired fins. Its locomotion is a series of traveling waves with the body forming a single wavelength for optimal efficiency [7]. Increases in speed are achieved by increasing the frequency of the traveling waves, but basically preserving the overall shape of the body. The pattern of motor output giving rise to the traveling waves is strict alternation of activity from the left and right sides within a single segment, and a traveling wave of excitation along first one and then the other side of the body. The activation of any two pairs of segments has a constant phase relationship regardless of the speed of propagation of the traveling wave (figure 2).

Study of the lamprey CPG has revealed a distributed chain of segmental oscillators, where each oscillator is no more than three spinal segments [9]. Each segmental oscillator has its

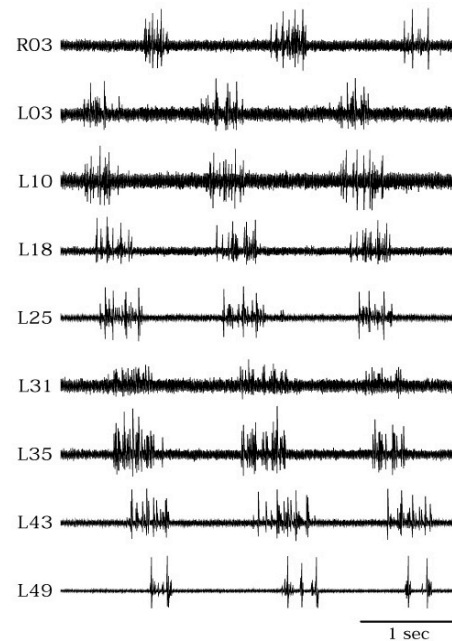


Figure 2: Lamprey traveling wave observed in isolated spinal cord

The motor outputs recorded from a 50 segments piece of isolated spinal cord bathed in excitatory neural transmitter (adapted from ref 8). The numbers denote the spinal segment in the isolated piece. The output at a single segment alternates (R03-L03), with a wave of activity descending down the spinal cord.

own intrinsic frequency under any given set of conditions [10]. These intrinsic frequencies differ among each other. The oscillators maintain a single frequency via coupling provided by a system of ascending and descending fibers that apparently make very strong connections overall. There is also evidence that the functional connections of the fibers can be made on segments nearby or upon segments up to more than 20 segments away [11]. The fiber systems are also distributed across the width of the spinal cord [12] (figure 3).

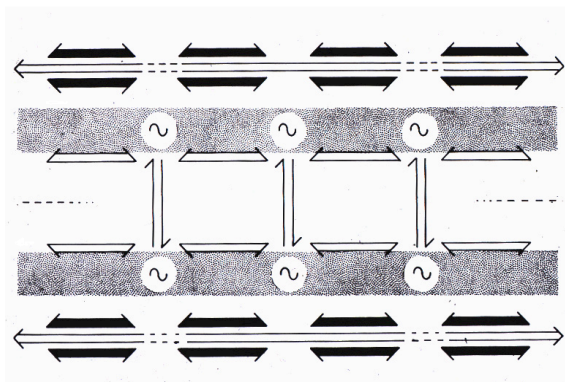


Figure 3: Functional organization of the lamprey CPG

Each segment or small group of segments consists of a pair of coupled oscillators. The coupling is ascending and descending, and long and short. (adapted from ref 12)

My colleagues and I have modeled the lamprey CPG as a chain of coupled limit cycle oscillators [13]. Coupling has been modeled as a periodic function of the phase difference between any two pairs of oscillators [13, 14]

With this view of the CPG in mind, Ralph Etienne-Cummings, Johns Hopkins University, designed an analog VLSI chip to produce periodic bursting to generate the rhythmic output of an actuator for the joint of a limb. The chip diverges in many ways from its biological counterpart, but captures the functional equivalence of the periodicity and strict alternation of a segmental oscillator (figure 4).

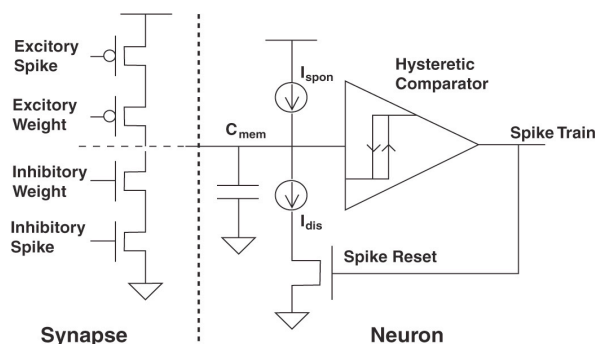


Figure 4: Circuit for CPG chip (from ref 15)

When two oscillators are used to control a pair of legs, coupling via mechanisms in keeping with the spirit of the earlier mathematical modeling is

effectively works to couple the pair of chips to maintain the limbs phase locked (unpubl. observation). Below, is further discussion of the basic chip and its interaction with sensory feedback from a bipedal limb robot designed by Anthony Lewis, Iguana Robotics.

An example of the use of the CPG to produce stable locomotion in a quadruped is seen in the robot, Tekken, designed by Hiroshi Kimura and his colleagues at University of Electro-Communications, Tokyo. It can generate a range of gait patterns and speeds of locomotion with remarkably smooth action [16].

2.2. Muscle co-activation

By contrast with the lamprey, the muscle activation pattern for limbed animals is not simple alternation, but is often co-activation of antagonistic muscles. Co-activation provides stiffness and stabilization of the joints. For example, during extension of a cat hindlimb, the extensors provide the propulsive force, but flexors are co-active to produce stabilization of the joint (figure 5: data from J-P. Gossard). Similarly, extensors are active during the end of flexion to brace the limb for the impact with the ground [17]. This pattern of co-activation is produced by the CPG of a functionally isolated spinal cord of the cat (figure 5), demonstrating that the pattern is intrinsic to the CPG and does not require sensory feedback or control descending from the brain. David Boothe [18] has shown several neural network models capable of generating this type of co-activation during rhythmic activity of a CPG.

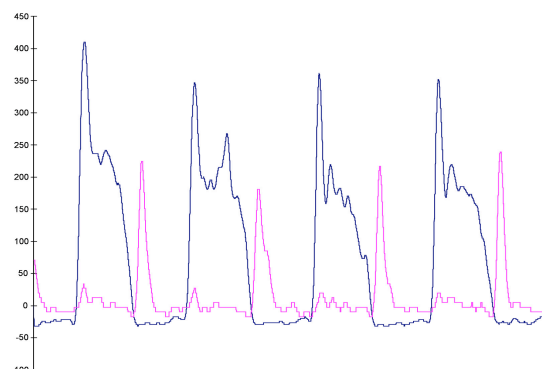


Figure 5: Co-activation seen in functionally isolated spinal cord of the cat

Recordings from flexor and extensor muscle nerves in a paralyzed cat with its spinal cord cut. Notice the flexors have a low level of activity during the phase of the cycle that extensors are active. Data from J-P. Gossard.

The use of co-activation is also shown in a robotic biped recently developed by Lewis (cf. Presentation by A. Lewis). The use of co-activation damps foot contact and provides increased control of the limb movements generally.

3. Sensory feedback

3.1 Resetting the step cycle

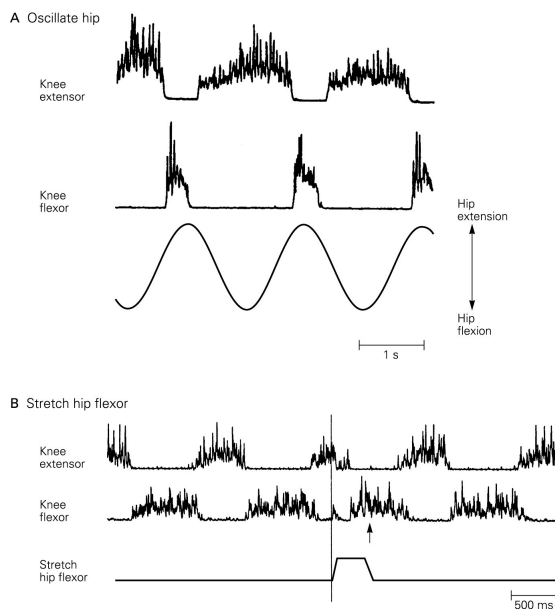


Figure 6: Hip joint entrains rhythm

Illustration of the entrainment of the CPG with sensory feedback (above) and the resetting of the step cycle (below): the recordings are integrated traces of muscle potentials recorded from a spinal cat. The feedback is stretch of hip muscle. Adapted from ref 4, with data from ref 19.

For all CPGs there is one or more critical feedback cue that triggers or resets a cycle period. This mechanism serves to adapt the cycle to the needs of the animal under all environmental situations. Phenomenologically, the sensory feedback entrains the locomotor

cycle [20]. In cats, it's been shown that several different muscles of the hindlimb can serve this purpose [19] (figure 6). In lampreys, stretch receptors located along the edges of the spinal cord itself serve this purpose. By bending the spinal cord directly, the stretch sensors can entrain the rhythm of the isolated spinal cord [21, 22].

In a biped with passive knees designed by Lewis and controlled by the analog VLSI chip of Etienne-Cummings, an angle sensor of the hip maintained the

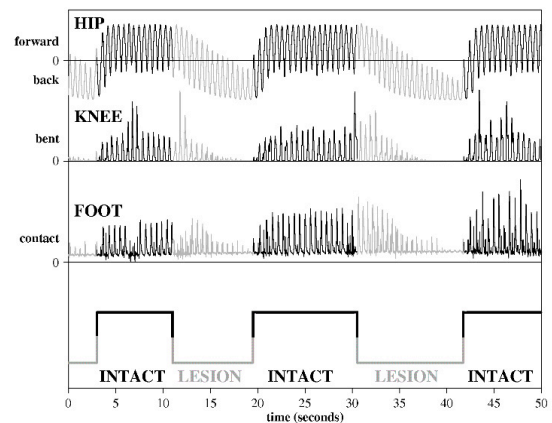


Figure 7: Biped joint angles with and without feedback

Joint angles with and without sensory feedback to reset the CPG chip: the dark lines indicate the joint angles when the feedback is on; the light lines when the feedback is off. Note how the angles drift away from a steady state when the feedback is off. (from ref 15)

limbs adaptively while walking on a treadmill. The chip was designed explicitly with a bias to prevent the biped from maintaining itself centered on the moving belt. Thus, with no sensors, the joint angles drift, while with the sensors on, they remain within a relatively stable range of values (figure 7). Through the use of the sensory feedback the biped attained a steady and stable gait [15].

Another example of this form of limb control in a robot is seen in Tekken, the robot developed by H. Kimura and his colleagues [16]. Control of

Tekken uses feedback from the limb to create mutual entrainment of the limb and the oscillator that controls it. The success of this kind of dynamic control is seen in the movies of Tekken (cf. H. Kimura presentation), as it walks up and down inclines and over irregular terrain.

3.2 Phase dependent corrections

To guarantee that movement is properly integrated with the environment, all sensory feedback is adaptively gated through the CPG. This means that corrections for perturbations of the limb are gated through the CPG during any form of locomotion. Reflexes that during rest are simple short latency responses of selective muscles, become more complex responses during locomotion. For example, the response to a perturbation to the walking limb will depend on the phase of the cycle during which it occurs. The simple reflex response to a painful stimulus applied to the bottom of the foot is withdrawal through activation of the flexors. However, if one limb is already off the ground when such a stimulus is given to the opposite limb that is in extension, the perturbed limb does not withdraw from the stimulus. Rather, the foot is driven harder onto the stimulus as a result of extensor activity [23], and the opposite limb is moved rapidly down to provide support. However, if the same stimulus is given while the foot is in its flexion phase, the flexors are, indeed, activated. Thus, the response adaptively adjusts to the phase of the step cycle.

In all CPGs, the same gating of reflexes is seen [24]. The response to a stimulus is adaptively filtered through the CPG to produce a phase dependent response to perturbing stimuli. H. Kimura and his colleagues demonstrate that this principle can effectively be applied to a quadrupedal robot to produce stable walking even when subjected to unexpected perturbations [16]. Cf. Kimura's presentation for dynamic integration of sensory feedback to step over obstacles and over irregular terrain.

3.3 Smart sensors – muscle stretch receptors

The typical stretch receptors for mammalian muscles, also offer potential for robotics. These receptors are part of complex structure called the spindle organ (cf. Ref 4 for overview and references). The stretch receptor itself is embedded in a small muscle fiber that is activated by specialized motor neurons (α -motor neurons) in the spinal cord that are situated among the motor neurons (γ -motor neurons) that activate the force producing muscle fibers. The spindle's motor neurons are often separately controlled and serve as part of servo-control system that regulates the excitability of the force producing muscles. Such control produces the unexpected result that the spindle receptors of some muscles are most active when its respective force producing muscle is at its shortest, that is, during contraction. This pattern of activity, while first shown in decerebrate animals has also been seen during locomotion of intact walking cats [25]. The reason for this counter-intuitive result, is that the activity of the spindle receptor neurons is responsible for activation of the motor neurons to the force producing muscles via synaptic connections of the spindle fibers directly upon the α -motor neurons. Thus, the spindle organs appear to be part of a servo-assist mechanism for the control of the force production in mammalian muscle. The output of the spindle stretch receptors is highly non-linear, as a consequence of the control exerted on the α -motor neurons. In reference 25, there are mathematical models that can predict the firing pattern of the spindle organs when controlled by α -motor neurons.

Importantly, a robotic spindle has been implemented and can replicate a great deal of the function of its biological counterpart [26]. Unfortunately, the robotic spindle has not yet been implemented with the activity patterns seen during mammalian locomotion. However, it would appear to contain the necessary structural complexity to produce the full range of behavior that has been documented to date.

It isn't clear that one needs or wants to include a full robotic implementation of the spindle in a robotic limb designed for walking. However, it's

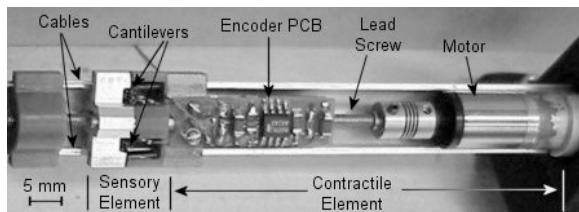


Figure 8: Spindle implementation by Jaax and Hannaford [26]

possible that one could use the control strategy of a non-linear control of force production for robotic actuators where the stretch receptors, in association with force receptors are used to control the activity of the actuators. Having some kind of complex non-linear control on the force production could potentially provide considerably more flexibility and sophistication in movement. Such a non-linear control strategy would not be the first order strategy, but could be a higher order improvement.

4. Summary and Conclusions

Presented here is an overview of some principles for control of locomotion that are seen in all animals and which offer ideas for robotic design and control. The intention of the overview is to suggest new ways to think about and to perhaps design legged machines taking inspiration and guidance from biology. Biological systems have had eons to find and develop optimal methods for control. An animal dies that fails to escape its enemies effectively because of a failure of its locomotor control system. The only control principles for locomotion that are seen universally are those that do allow animals to escape and procreate. Examples are given in which the principles have been applied successfully to limbed robots. The application of the biological principles makes the implementation of the robotic locomotion remarkably smooth and adaptive to most conditions including irregular terrain and random perturbations. Kimura's dynamic integration of sensory input with a limit cycle oscillator provides an example of a robotic system that puts all the pieces together. The movement of Tekken speaks for itself.

Additional suggestions are also provided for potential new approaches that one might consider for legged robots. These suggestions come from less universal features of motor control, but features that nonetheless may offer novel perspectives. The use of co-activation of actuators acting across a single joint, and complex non-linear integration of sensory feedback could offer more flexibility and optimality in both bipedal and quadrupedal machines.

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