Sensorimotor Integration in Lampreys and Robots II: CPG Hardware Circuit for Controlling a Running Robotic Leg

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Abstract- *We present a silicon chip realization of a basic unit of locomotor control: the Central Pattern Generator(CPG). This chip is very low power, uses a minimum of chip space, and can be manufactured inexpensively. Although the control systems of robots and animals were designed by different agents, it appears that a common computational paradigm, adaptive non-linear dynamical systems, yields efficient implementations in both natural an artificial systems. Here we give an overview of a chip that implements this emerging computational paradigm.*

The chip uses 3 adaptive mechanism: (1) Firing rate adaptation— In the absence of sensory input the output motoneurons have a stable firing rate; (2) Phase resetting— 'stretch receptor' feedback can entrain the CPG's oscillator; (3) Interspike interval adjustment— compensates for dynamic variations in the mechanical system.

1.0 Introduction

Both roboticists and biologist have an interest in understanding the principles of locomotor control. Although natural agents and synthetic agents are studied under different disciplines in the artifice of human organization, they both must adhere to the same strict physical principles dictated by nature.

Evolutionary pressures largely dictate the design of the internal control systems of natural agents. The designer chooses the control systems of robots.

Walking machines and locomotory animals encounter the same fundamental problems such as postural control, coordination of contact points (limbs or body surface), coordination with the environment using distal sense (e.g. visuomotor coordination). Both systems would benefit from compact, efficient controllers that minimize energy usage and volume.

Even though these systems have different designers, a common level of abstraction for both the study of locomotion and its control may certainly be possible.

In this paper we present a recent work in creating a synthetic control element— a central pattern generator (CPG) chip— that mimics some properties of the basic functional unit of natural control system, yet has the potential for being the most efficient control system for synthetic agents yet proposed.

It is well recognized that the physics of silicon is in many ways analogous to the biophysics of the nervous system [1]. Therefore, neuromorphic systems are often implemented in silicon using as much of the properties of device physics as possible.

We show that the circuit, consuming less than one microwatt of power and occupying less than 0.4 square millimeters of chip area (using 1.2 micron technology), can generate the basic competence needed to control a robotic leg running on a circular treadmill. Furthermore, the circuit can use sensory feedback to stabilize the rhythmic movements of the leg.

Potentially, this technology could provide inexpensive circuits that are adaptable, controllable and able to generate complex, coordinated movements. Such circuits could be used in miniature systems to modulate repetitive cyclical movements based on appropriate sensory feedback. These systems could include miniature walking, running, flapping and swimming machines.

The following is largely a synopsis based on [2]. The reader is referred to the companion article for a review of the principles of locomotor control in vertebrates.

1.1 Modeling CPGs on a Neuromorphic Chip

CPGs are most often modeled as distributed systems of non-linear oscillators. In our implementation the basic coordination in the leg is achieved by phasically coupling two neurons together to achieve oscillations. When coupled together they are alternatively active. This alternating activity is the basic coordination needed to drive the hip of the robot. A phase control circuit governs the phase difference between the neurons. These oscillator neurons drive two integrate-and-fire motoneurons.

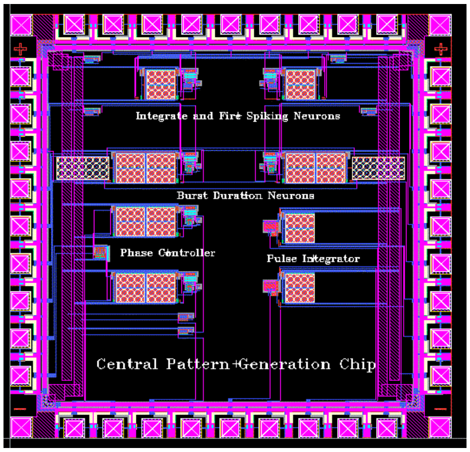

Figure 1. Layout of the CPG chip. Each component is wired to pins to facilitate the prototyping of oscillator circuits.

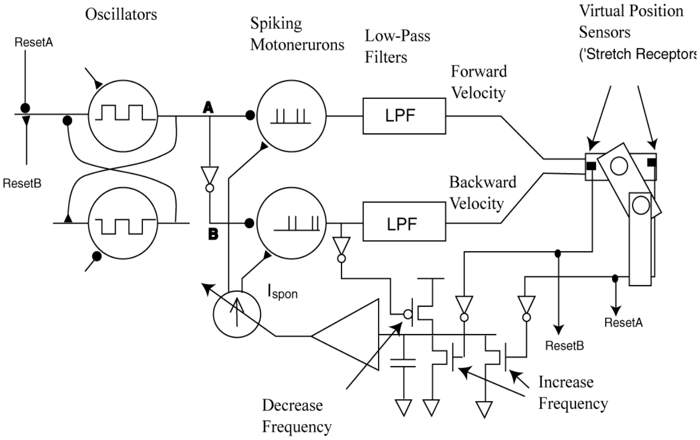

Figure 2. Adaptive control of a limb's dynamics using a neural CPG with learning capabilities.

In our experimental setup, the robot under control uses servomotors. To be compatible with this technology, it was necessary to low-pass filter the spiking neurons and then integrate the resulting smooth graded velocity signal.

We will show the circuit in autonomous operation and with sensory feedback from 'stretch receptors' used to reset the CPG. We also demonstrate a property of our biomorphic leg: we show that our limb and its control circuit not only produce stable rhythmic motion, but can also compensate for intentional chip biases, environment disturbances, as well as mechanical complexity of an active hip and passive knee.

2.0 The CPG Chip

The CPG chip is designed to provide biologically plausible circuits for controlling motor systems. The chip contains electronic analogues of biological neurons, synapses and time-constants. In addition, the chip also contains dynamic analog memories, and phase modulators. Using these components, non-linear oscillators, based on the central pattern generators of biological organisms, can be constructed.

The dynamical properties of the neural circuits can also be adapted using direct sensory information. In this first version of the chip, shown in Fig. 1, all the components are individually accessible such that they can be connected with off-chip wiring to realize any desired circuit. In future versions, tested neural CPG circuits will be integrated with completely hardwired or programmable circuits.

2.1 The Hardware Components

In this section we describe the basic elements of the CPG chip: the spiking motoneuron, the graded response neuron and the (CPG) oscillator.

2.1.1 The Spiking Motoneuron

Our neurons use an integrate-and-fire model. A capacitor, representing the membrane capacitance of biological neurons, integrates impinging charge. When the "membrane-potential" exceeds the threshold of a hysteretic comparator, the neuron outputs high. This logic high triggers a strong discharge current that resets the membrane potential to below the threshold of the comparator, thus causing the neuron's output to reset. This circuit therefore emulates the slow phase and fast phase dynamics of real neurons. The process then starts anew.

2.1.2 Graded Response Neuron

In addition to spiking neurons, we make use of neurons with graded response. These neurons are essentially the same as the spiking neuron except that the hysteretic comparator is replaced with a linear amplifier stage and no feedback signal is used.

2.1.3 The Oscillator

The neural circuits for creating the CPG are constructed using cross-coupled square-wave oscillators. The output of these oscillators drives the bursting motoneurons. A master-slave configuration of the neurons allows us to construct an oscillator with a constant phase relationship. By setting the excitatory and inhibitory weights to equal values, a square-wave with a duty-cycle of 50% is obtained. The phase relationship between the two sides can be varied. The frequency of oscillation is set by the magnitude of the weights. This asymmetrically cross-coupled oscillator serves as the basic CPG unit that can be modified according to the application. By injecting or removing charge from the membrane capacitors of the oscillator neurons, the properties of the CPG can be altered.

For the experiments described here, a 180 degrees phase relationship is required. Hence an inverted version of one of the oscillators is used, as shown in Fig. 2.

2.1.4 The Neural Circuit

The complete neural circuit is given in Fig. 2. The output of the basic oscillator unit is used to inhibit the firing of the spiking motoneuron. When the oscillator output is high, the motoneuron is not allowed to fire. This produces two streams of 180 degrees out of phase spike trains. These trains can be low-pass filtered to get a voltage which can be interpreted as a motor velocity. Consequently, the oscillator controls the length of the motor spike train, while the spike frequency indicates the motor velocity.

The spike frequency is regulated by a feedback loop. Spiking places charges on the neuron membrane capacitor seen in the lower part of Fig. 2. The integrated charges are buffered and then used to down-regulate spike frequency. In this way spike frequency is less sensitive to component variations.

In the next section we describe two additional sensory mediated loops that adapt the oscillator and the motoneuron spiking.

2.2 Sensory Adaptation and Learning

2.2.1 Adaptation based on a 'stretch receptor'

As shown in Fig. 2, the oscillator neurons can be stopped or started with direct inhibitory and excitatory sensory inputs, respectively. When the inputs are received as strong inhibition, the membrane capacitor will be shunted and discharged completely. It will remain in this state until the inhibition is released, then the normal dynamics of the oscillator will continue from the inactive state.

Alternatively, if the sensory input is received as a strong excitation, the oscillator will be driven into an active state. When the excitation is released, the oscillator will continue from the active state. Clearly, the charge-up or discharge of the membrane capacitor will be influenced by any direct sensory input. If the sensory inputs are periodic, the oscillator outputs can be driven such that they are phase locked to the inputs.

We use this property to mimic the effect of the stretch reflex in animals. When the leg of an animal is moved to an extreme position, a special sensor called a stretch receptor sends a signal to the animal's CPG causing a phase resetting. This is mimicked in the circuit presented here. Referring to Fig. 2, the leg may reach an extreme position while still being driven by the oscillator. In this case, a virtual position sensor, which mimics a stretch receptor, sends a signal to *ResetA* or *ResetB* to cause a resetting of the oscillator circuit as is appropriate to cause a hip joint velocity reversal.

2.2.2 Spike Frequency Adaptation

The chip provides a short-term (on the order of seconds) analog memory to store a learned weight. Clearly, this architecture favors a continuous learning rule. Spikes from the motoneurons are used to increase or decrease a voltage on the capacitor of a graded response neuron. In the absence of the training inputs, the stored weights decay at approximately 0.1V/s. Figure 2 shows a schematic for adapting the spiking frequency of the motoneurons based on the swing amplitude of the limb.

3.0 Experimental Setup

The experimental setup consists of a small robotic leg, the CPG chip, necessary components to interface the chip to the robotic leg, a rotating drum treadmill and data collection facility.

The robotic leg is a small (10-cm height) two-joint mechanism. In our setup, only the "hip" is driven. The "knee" is completely passive. The knee swings freely, rotating on a low friction ball-bearing joint. A hard mechanical stop prevents the knee from hyperextending.

The leg runs on a drum that is free to rotate under the contact forces of the leg. As the leg pushed backward on the drum it sets the drum spinning

The robotic leg has three sensors on it. These sensors measure the angle of the hip and knee joints as well as force loading on the foot. The hip sensor is also processed to produced a 'stretch receptor' type of signal. The chip is integrated into the system as shown in Fig. 2.

4.0 Experiments

4.1 Running with a passive knee

In this experimental setup, the CPG circuit drives the actuator in the hip joint. The knee joint is passive and rotates with very little friction. The assembly is suspended above a rotating drum. The CPG circuit is started.

Data is collected from three sensors: Foot pressure, knee and hip. 'Stretch receptor' sensory feedback from the hip is used as feedback to the CPG.

4.2 Sensory feedback lesioning

This experimental setup is similar to the first experiment. The difference is that sensory feedback is lesioned (turned off) periodically. We collect data as before.

5.0 Results

5.1 Running Results with a Passive Knee

A remarkable feature of this system is that the knee joint adapts the correct dynamics to enable running (!). The natural dynamics of this particular system allow the lower

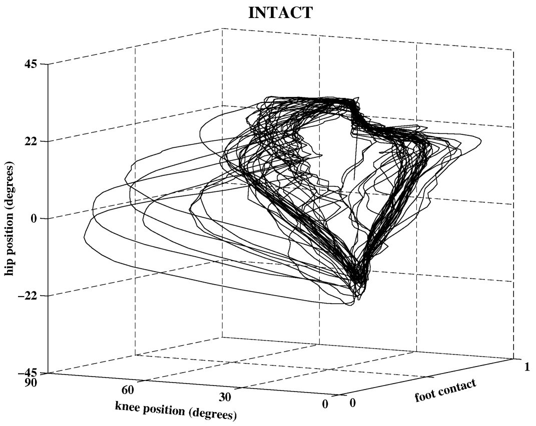

Figure 3. Hip, knee and foot-contact phase diagram. Most of the trajectory is in a tight bundle, while the outlying trajectories represent perturbations.

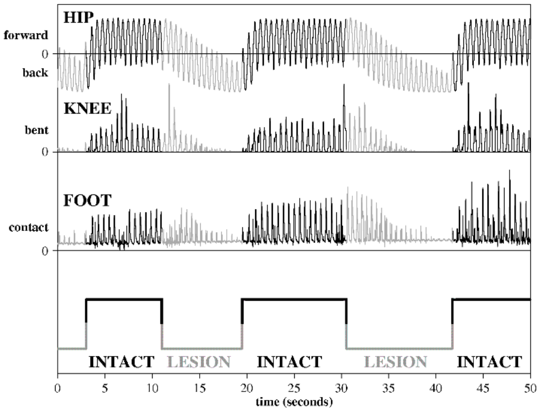

Figure 4. This figure shows the effect of lesioning sensory feedback. When the feedback is lesioned (Time 11-19 seconds and 31-42 seconds), the hip drives backward significantly. As it does the foot begins to lose contact with surface and the knee stops moving. When the lesion is reversed at 19 and 42 seconds, the regularity of the gait is restored.

limb to be driven in coordination with the higher limb, even though the knee is passive.

A phase plot of the knee, foot and hip position and foot contact is shown in Fig. 3. The bulk of the trajectory describes a tight 'spinning top' shaped trajectory while the few outlying trajectories are caused by disturbances. After a disturbance the trajectory quickly returns to its nominal orbit and we can infer that the system is stable.

5.2 Lesion Results

Next we lesioned the sensory feedback to the leg periodically. Figure 4 shows the effect of lesioning on the position of the hip and knee joints as well as the tactile input to the foot. After lesioning the leg drifts backward significantly due to a bias built into the chip. When the sensory input is restored, the leg returns to a stable gait.

5.3 Gait Stability

Perturbations to the leg cause momentary disturbances. As seen above in Fig. 3, several of the trajectories are clear "outlyers" to the typical orbit, and result from environmental disturbances.

We found that sensory feedback could compensate for both the bias of the chip and environmental perturbations.

6.0 Conclusions

In this paper we present a hardware implementation of a CPG model. Our custom aVLSI chip, having only 4 neurons and occupying less than 0.4 square mm, has the basic features needed to control a leg running on a treadmill.

We conclude that the control of a running leg using an aVLSI CPG chip is possible. We demonstrate that, at least in this experimental setup, running is possible using an under-actuated leg. Finally, we demonstrate a basic adaptive property of phase resetting using a stretch receptor.

It should be emphasized that the system being controlled is non-linear and the chip itself uses non-linear elements to control it. We have a coupled system of non-linear elements. We make no attempt to linearize the system. Instead we take advantage of the non-linearities.

Because (1) we do not make use of models, or linearization, (2) we adapt principles from biological systems, and (3) these principles can easily be implemented with low-power integrated circuits, we are able to achieve a very compact solution. Further experimentation with this system will allow us to determine if a robot can be made to walk by coupling together multiple circuits of the type presented here. The current results, however, are promising.

Acknowledgements

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[2] M. A. Lewis, R. Etienne-Cummings, A. H. Cohen, and M. Hartmann, "Toward Biomorphic Control Using Custom aVLSI CPG Chips," presented at 2000 IEEE Inter Conf on Robotics and Automation, San Francisco, 2000.