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Low power CMOS electronic central pattern generator design for a biomimetic underwater robot

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Abstract

This paper presents a feasibility study of a central pattern generator-based analog controller for an autonomous robot. The operation of a neuronal circuit formed of electronic neurons based on Hindmarsh–Rose neuron dynamics and first order chemical synapses is modeled. The controller is based on a standard 0.25 μm CMOS process with 2 V supply voltage. In order to achieve low power consumption, CMOS subthreshold circuit techniques are used. The controller generates an excellent replica of the walking motor program and allows switching between walking in different directions in response to different command inputs.

The simulated power consumption is 4.8 mW and die size including I/O pads is 2.2 mm by 2.2 mm. Simulation results demonstrate that the proposed design can generate adaptive walking motor programs to control the legs of autonomous robots.

Keywords: Subthreshold operation; Central pattern generator; Electronic neuron circuit; Electronic synapse circuit; Neuronal oscillator circuit

1. Introduction

Robots are fundamental in a broad spectrum of repetitive or dangerous work efforts ranging from industrial to field applications. Most contemporary robots, however, can operate only in simple structured environments. There is a strong demand for consumer, industrial, and scientific applications for autonomous robots that can operate adaptively in unpredictable environments. Existing robots are commonly controlled by algorithm based systems such as finite state machines [5]. However, algorithm-based robots controlled by digital processors may adapt poorly to unstructured environments due to an inability to anticipate all contingencies. Animal models provide proven solutions to the problem of adaptation to field environments and the underlying neuronal mechanisms are understood adequately to allow construction of neuronal circuit-based controllers [4]. As a result, some investigators have focused on emulation of biological nervous systems through biomimetics [2].

The innate behavior of animals is controlled by central pattern generators (CPGs) resident in central ganglia or the spinal cord [7]. It is our contention that if CPG-based controllers are imitated, many problems due to deterministic control program can be solved and it will be feasible to develop an adaptive autonomous robots that operate with flexibility in natural environment. CPGs can be constructed from electronic neurons based on non-linear dynamical models of biological neurons [16]. However, these circuits are built from discrete components and are not a realistic solution due to their size and power.

The basic concept of the CPG and its architecture are reviewed in Section 2, and its sub-blocks are discussed in Section 3. Section 4 demonstrates the electronic CPG circuit followed by the HSPICE simulation results in Section 5. Finally, Section 6 concludes the paper.

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2. Central pattern generator

CPG are normally turned and modulated by descending motor commands and coordinated among themselves by coordinating neurons that provide a governed oscillator with information about the activity status of a governing oscillator to maintain gait [18]. During locomotion the motor programs generated by CPG are modulated by sensory feedback. Depending on the locus of action of the sensory feedback within the CPG it can either modulate the amplitude of the output or reset it's timing to adapt to environmental contingencies.

Some researchers published interesting works recently. Simoni et al. [17] presented an analog integrated circuit architecture to implement the conductance based dynamics that model the electrical activity of neurons. The implementation was designed to model the leech heart (HN) interneuron. However, they did not focus on low power technique and low power consumption constraint is not met entirely. Arena et al. [1] presented CNN (cellular neural network) based chip for robot locomotion control. The circuit was implemented using switched capacitor filter circuits that require other circuit overhead such as clock generator and clock distribution network. This causes not only hardware and area overhead but also digital switching power from the clock switching. The circuit technique works only for very low frequency operation. Furthermore, they used ±4 V power supply, which is not suitable for low power operation. Another implementation approach is to use programmable array as shown in [19]. They implemented an array of programming silicon neuron. However, they tried to generate required waveforms to emulate a biological CPG resulting in a poor dynamics of the neuron properties.

We have been developing robots based on this low power CPG model [2]. Our lobster-based platform is intended for remote sensing applications in the littoral zone. This robot features a physical plant based on the lobster body, artificial muscle fabricated from shape memory alloys, neuromorphic sensors and a controller based on known lobster circuitry [3].

Fig. 1 represents the core of the CPG for control of the walking movements of one leg. The four interneurons form the neuronal oscillator for the four-phase rhythm and two of these interneurons (*elev* and *dep*) directly activate motor synergies that control the elevation/depression movements of the coxo-basal (CB) joint. The other two interneurons (*swing* and *stance*) activate both antagonistic motor synergies that control the thoraco-coxal (ThC) and merocarpopodite (MC) joints of the leg. The interneuron timing circuit enclosed by the dashed square is activated by a parametric command that corresponds to the bias current (*i*) in the electronic circuit. This parametric command gates on the oscillator and controls it's average frequency. The motor synergy neurons are activated indirectly by excitatory input from the interneurons. The four phase rhythm emerges from the pattern of inhibitory synaptic connectivity between the interneurons. *Elev* serves as a pacemaker to determine the frequency of stepping movements and inhibits both *dep* and *stance*. The burst of spikes in *elev* defines the duration of the early swing phase of the step cycle. Intrinsic parameters of the *stance* EN are adjusted so that stance bursts at a slightly slower endogenous frequency than *dep* and the time constant of the inhibitory synapse between *elev* and *stance* is increased so that there is a delay between the onset of *dep* and *stance*. This delay forms the late swing phase of the step cycle. In inhibitory connection between *stance* and *swing* ensures that swing is active during the early and late swing phases and silent during the stance phase. A second layer of command (*forward*, *backward*, *leading* and *trailing*) controls the direction of stepping by gating off the appropriate connections between the swing and stance interneurons and the motor synergies. For example, during forward walking the connections between *swing* and retraction (*retractor*) and *stance* and protraction (*protractor*) are gated off. During forward and backward walking, the commands for the MC joint are not gated so that the antagonistic extensor (*extensor*) and flexor (*flexor*) are coactivated to keep the joint stiff. Similarly, during lateral walking, the *protractor* and *retractor* synergies are coactivated to keep the ThC joint stiff.

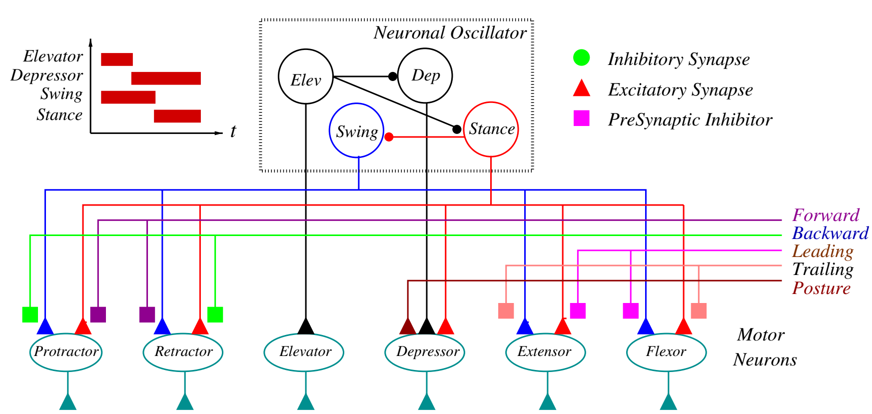

Fig. 1. The block diagram of central pattern generator.