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Bio-inspired coupled oscillatory phase reset control system applied to movement in an underwater vehicle

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HIGHLIGHTS

- Motor control based on intrinsic oscillation in vertebrate neurons is implemented.
- The vertebrate olivo-cerebellar network constitutes the core of the design.
- The model is used to control an underwater vehicle movement.
- Video camera controls movement by system oscillation phase resetting.

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ABSTRACT

The present hardware circuit was designed as a fast and energy efficient motor control system based on cerebellar oscillatory neuron activity and network dynamics. Specifically, a hardware model of the olivo-cerebellar dynamics controlling vertebrate motor coordination is used to control movement in an underwater robotic vehicle. Single shot oscillatory phase resetting is used for instantaneous motor plant reorganization based on incoming sensory information. Such a rapid feedback mode, which is rapid enough to prevent animals from falling when they stumble, has been previously described in biological and mathematical papers (Pellionisz and Llinas, 1979, Velarde et al., 2002, 2004). In the present control system, the direction of the vehicle displacement is captured by a camera, and transformed into a phase shift modulation of sets of oscillatory elements that embody internal dynamics. This design provides a novel real time control platform for robotic control in three dimensions.

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1. Introduction

This paper introduces an analog hardware system (AHS) that mimics biological control of motricity. The device emulates the dynamic properties of the olivo-cerebellar control network in vertebrates [1], and is capable of autonomous motor guidance using oscillator based paradigms. The motivation in developing such a control system was twofold: (1) to provide a heuristic tool to test biologically derived control paradigms and (2) to develop simple, energy efficient damage impervious control systems that may be used in robotic motricity. Our control system relies on a non-conventional three-axis tensorial model [1] of variable sine wave patterns to control motion. The present embodiment is designed to track a moving light source that provides a robot with allocentric movement directionality. The sensory input is supported by a CMUcam2 [2] running on an input interface and a centroid algorithm, which determines the center of mass of the light source. In order to test the actual control properties of this system our device was thus incorporated into a Bio-inspired Autonomous Underwater Vehicle (BAUV) developed by our colleagues at the Navy to explore underwater robotics. This robot is equipped with two sets of three fins, one set at each end of the vehicle's body [3–6]. Each fin is equipped with two-step motors to allow frequency, pitch and amplitude control. The "visual" information provided by the camera is introduced into a pattern generator based on a three-axis tensorial model [7]. The generator determines the individual contribution of each fin in an input-specific manner allowing correct movement execution *even in the absence of any other fin or fins*. The actual movement is implemented by a set of "motoneurons" that transform pattern generator output into pulse width code and delivers it to the step motors through a serial port interface.

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Thus, each motor is continuously activated in accordance with the contribution it should provide to the overall movement of the vehicle at a given instant.

2. Background

Biologically based control systems have evolved to reduce, to a controllable set, the nearly infinite number of possible solutions to a given motor outcome. With over 600 skeletal muscles and about 200,000, motor units supporting an astronomical number of degrees of freedom, the vertebrate CNS must accomplish a large volume of processing in real time. For example, a vertebrate arm with an arbitrary number of 50 muscles across three joints and a time delay of control of 1 ms would have $10 \times {}^{15}$ possibilities per movement to reach a desired target. In addition, it would require a $10 \times {}^{18}$ combination just to discriminate which of the $10 \times {}^{15}$ possibilities of movement is more adequate. Such a calculation would only be possible with a brain operating at a frequency on the order of 1 EHz (1 million GHz) [8]. Clearly these numbers do not correspond to the biological solution given that the human brain has $10 \times {}^{11}$ neurons, of which only a fraction contribute to motor control.

A different approach in which non-continuous or discrete control is used, significantly reduces processing burden by increased efficiency and break onset inertia during acceleration by increasing synergy. This approach can be implemented by small groups of hardware neurons where the 'combinatorial' power and speed of processing of the system would be immensely increased in speed and reliability.

Issues that have arisen regarding control optimization from biological research indicate that, given the visco-elastic resonance dynamic of limbs [9], neuronal subthreshold membrane potential oscillation of 5–10 mV at 8–12 Hz [10,11] optimally damps motor actuator discontinuity. It is also clear that neuronal subthreshold oscillation and abrupt oscillatory phase controls are optimal in organizing multiple moto-neuronal subsets rapidly in a pulsatile/synergic movement control device [12]. It is also clear that the use of oscillation and reset coupling for movement control postulated [13–16] corresponds, in vertebrate brain, to the fundamental properties of the olivo-cerebellar system.

The olivo-cerebellar system

A short description of the inferior olive (IO) control system in vertebrates would include an electrophysiology perspective of IO subthreshold membrane potential oscillations (Fig. 1A). This cell property confers intrinsic time restricted excitability such that the neuron fires action potentials only if an input arrives with a certain phase shift value [16]. Its membrane characteristics and connectivity combined with a recurrent electrical coupling controlling loop (IO → PC → IO) give the IO unique dynamic properties, making it an ideal rapid motor-control system [17,18].

At the multicellular level IO cells are organized into coupled cell assemblies (glomeruli) that permit highly organized patterns of synchronous firing at the cerebellar Purkinje cell level [20,19]. Assemblies of cells are electrotonically coupled and such coupling is regulated by an inhibitory input from the cerebellar nuclei [21,22]. Taken together these cellular and subsystem properties allow high dimensionality movement problems to be modulated within units of oscillation, rather than at basic cellular processing speeds.

The basic functional properties of the IO are utilized here as the central controller implementing resettable motor patterns. These motor patterns are rapidly modulated by oscillatory phase resetting [16] combined with controlled electric coupling [23]. Specifically, weakly chaotic [24] membrane potential oscillations neither allow phase shift without modifying amplitude nor reentrance frequency [15]. Furthermore, the stability of electrical coupling is quite remarkable. Indeed, it can support linear phase shift reset independently from its initial phase while maintaining the chaotic non-linear subthreshold oscillation and their coupling resonance [15]. Mathematical modeling implementing the control properties of multilayer structures simulating IO nuclei dynamics has been demonstrated [14,19]. Such modulations allow the formation of well-organized neuronal activity patterns that can serve as the dynamic substrate in motor coordination.

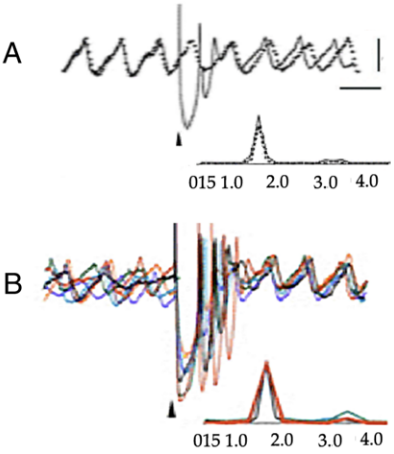

Fig. 1. Single cell oscillations in the olivo-cerebellar system recorded in vitro. (A) Intracellular recording of spontaneous IO neuron oscillation, interrupted by an extracellular stimulus (arrowhead), delivered to the dorsal border of the IO nucleus. Following stimulation, the oscillations were interrupted for 750 ms before resuming at a different phase. (B) Superposition of six (color-coded) individual intracellular traces of stimulus-evoked oscillations (as in A) are superimposed. Note that following the electrical stimulus the oscillatory phase is shifted independently from the oscillatory phase at the time of stimulus onset, but resumes at a very similar phase.

Source: Calibration bar: 1 mV; 1 s, taken and redrawn from [19].

From the above, it has been proposed that the olivo-cerebellar system may be viewed as a set of phase-coherent oscillatory clusters, where the clusters' dynamic spatial configuration directly corresponds to a particular movement (as groups of muscular group activations). Thus ongoing cluster dynamics "choose" the optimal motor configuration for the next time step and implement predictive control [25]. Such internal representation of the parameter space provides the system with a high degree of functional heterogeneity. Indeed, the olivo-cerebellar controller can implement a single oscillatory cluster phase reset and can even execute the required action in the presence of a damaged unit. From this perspective, the olivo-cerebellar controller does not "compute"; rather, it deals with analog signals and represents the parameters under control (muscles) as space–time patterns (motor patterns).

Beyond phase resetting, the IO takes advantage of a second additional form of control, by modulating electrical coupling through inhibitory input from the cerebellar nuclei [26]. It is known from electrophysiological studies that the reset properties of the IO are very fast and that it can reach as many neurons as connectivity allows. In this case, then, motor action is determined by the timing of the reset signal in olivary neurons [19]. A final issue relates to phase drifting due to the dynamic properties of the oscillators and the low impedance current leakage via coupling with other neurons [11]. In our case, however, low coupling impedances support the functional transitions, as a consequence of cycle dynamics itself, supporting further recurrent feedback transitions.

Using a Hopfield configuration [27] (Fig. 2) the number of oscillators defines the functional outputs of the structure but, significantly, not the number of possible internal states [28,29]. The electrical coupling between oscillators modifies transmembrane impedance load as well as the degree of connectivity with other neuronal elements and, therefore, changes both ensemble dynamics and their phase difference. Because the variation between

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