A network of spiking neurons develops sensorimotor mechanisms while guiding behavior.

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Introduction

Emulating animal movement in artificial models is informative about brain organization as well as being useful. One application of neuromorphic engineering is to control maneuverable robots using compact, low power circuits fabricated in VLSI. The silicon "neuromorph" developed in our laboratory is a neuron analog with a branched dendritic tree activated by spikes (1). The dendrite responds with postsynaptic potentials that diffuse towards a soma, generating a spike train output. The problem is how to arrange networks of such units to perform behavioral tasks. Designing connections is difficult given the richness of potential connections and choices of synaptic and other neuronal mechanisms. Animals' nervous systems accomplish this largely by self-organization during development. The objective is to explore ways of doing this in a neuromorphically-controlled robot that develops neural connections while behaving. The biological prototypes that inspire this effort are fishes, whose brains develop continuously throughout life while behaving adaptively. The work to be reported makes contact at several points with behavioral and physiological data from these animals (3, 4).

Neuromorphic system

Artificial dendritic tree neuromorphs are embedded in a purpose-built, digital spike-distribution system ("Virtual wires" (1)). Spikes afferent to the dendritic tree of a neuromorph generate transient postsynaptic potentials that are either excitatory (+ve going) or inhibitory (-ve going). The combined potentials are fed to an integrate-and-fire soma. Immediately after the soma fires a spike, its firing threshold rises and then decays, providing refractoriness. The passive, compartmented dendritic trees impart delays and attenuation depending on the site of synaptic activation, and exhibit non-linear, dendritic saturation (1). Software simulations are also explored in a simplified implementation based on the Spike Response Model (2). In both implementations, synaptic efficacy is controlled by numeric weights and all communication between neuromorphs is via spikes with programmable axonal delays. A Hebbian learning rule is employed: synaptic strengths being increased or decreased depending on a function of the time interval between pre- and postsynaptic spikes (2). Weights are subject to normalization and decay, settling to stable values. When enabled, learning continuously updates weights during a behavioral run. Neuromorphs are typically biased so that on average only a few individuals of a pool are firing at a time – and therefore learning.

The robot and its environment

The robot's two external sensory systems comprised of whiskers and a compound eye sense the frontal 120 degs in the horizontal plane. Each whisker responds with trains of spikes at a frequency proportional to their overlap with an obstacle. The eye consists of an array of 12-

24 receptors with Gaussian receptive field profiles. The receptors generate non-adapting analog signals proportional to their light capture that are fed to several layers of neurons - "retinal ganglion cells" - each with various sustained/transient, and on/off response properties. Additional spikes – "motor efference copies" - signal rotation and translation movements of the robot. All these spikes project via delays and modifiable weights to one or more layers of spiking neurons - the "tectum". In fishes this important sensorimotor structure controls steering and locomotory movements. In the model tectum, half of it controls left turns, half right turns. The rate of spiking determines the turn angle. The environment contains obstacles of various sizes and reflectances, and barriers with openings. The robot's task is to navigate in a northerly direction through the obstacles without making contact with them. During developmental experience, unit receptive properties are explored with various kinds of stimuli and compared with electrophysiological data.

Developmental training
Development starts with the whisker weights preset to elicit contraversive turning when stimulated. With this reflex, the robot feels its way, often getting stuck between obstacles. Visual spikes are converged onto the "tectum" via Hebbian synapses; those synapses responding just before and during whisker activation modify in strength. The result is a visuotopic map across the tectum. With suitable biasing, the visual input alone becomes capable of guiding the robot through the obstacles with greater anticipation, and therefore fewer blockages than with whiskers alone. Luminance contrasts turn out to be sufficient for simple obstacle avoidance, but navigation through more complex environments requires motion cues. Rather than designing motion sensors, selectivity for motion was developed through experience. Retinal units were projected onto the tectum via weights with a range of axonal and/or dendritic delays. Running the robot through the obstacle course developed weights that responded somewhat selectively to approaching objects, but over large areas of the visual field. Obstacle avoidance was not noticeably improved.

Better use of motion cues, as in the negotiation of gaps in textured barriers, depends on analysis of motion flow fields, requiring the elaboration of small, directionally selective receptive fields distributed over the visual field, as exist in tectum. This can be accomplished in a single layer by converging (a) transient visual units, whose synapses are modifiable, together with (b) sustained units, topographically mapped by experience as above, and (c) a motor efference copy signaling direction of eye rotation. Interestingly, this same combination of signals occurs in fish tectum: the retina sends (a) transient visual information directly to tectum; the torus longitudinalis indirectly sends (b) topographic, sustained luminance information to tectum together with (c) directional eye movement information (3). Other insights accrue from modeling spiking neurons. The propensity of neurons in tectum to synchronize (4) leads to a plausible model that attends selectively, an important capability for behaving hardware.

References

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