A CMOS IMPLEMENTATION OF A NEURAL NETWORK FOR UNDULATORY LOCOMOTION IN C. ELEGANS

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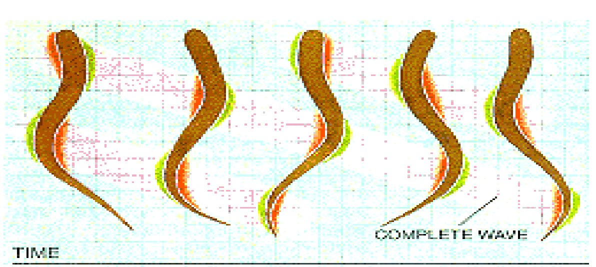
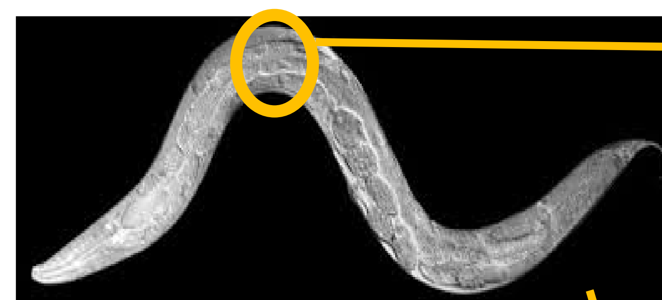
Introduction

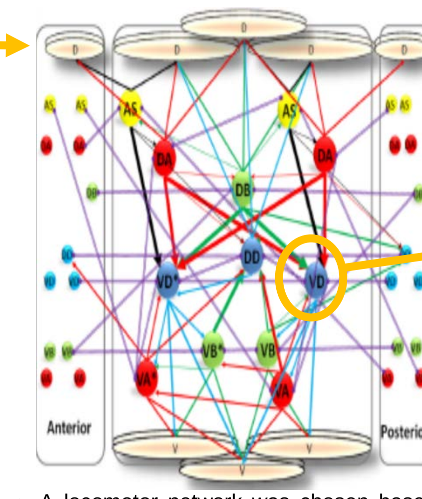
With an ultimate goal of making the first complete biomimetic physical neural network, we started building and simulating the locomotor neural network of a small worm, C. Elegans.
Central Objective: Design and simulation of Biomimetic CMOS Circuits to replicate undulating motion and touch based locomotion in Caenorhabditis Elegans.



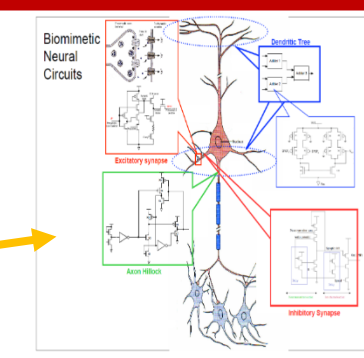
Biology and Neural Circuitry



- C. Elegans has a total of 302 neurons.
- It lacks a brain but has a ganglion.
- A full connectome has not been developed due to plasticity and loss of effectiveness of laser ablation experiments as the worm develops in to an adult.
- The worm has separate Dorsal and Ventral musculature which are responsible for movement.
- The worm responds to touch; stimulus applied to the head causes backwards motion and applied to the tail causes forwards motion.
- Motion in the worm follows an undulatory model in which the worm lies on either the sinister or dexter side to crawl or swim.



- A locomotor network was chosen based on iterated connections throughout the body of the worm [1].
- A threshold of 2 was set and connections that appear more than twice in the partial connectome were kept in the stage (mimicking nerve rings) which is then repeated six times to make the complete worm.

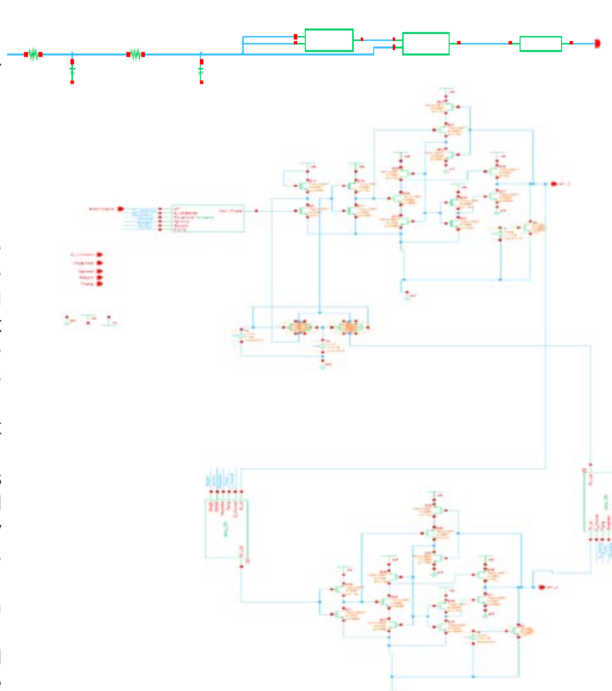


- A neuron is typically composed of the soma or cell body, dendrites and axon.
- Synaptic signals are received by the soma and dendrites and signals to other neurons are transmitted through axons. A synapse (an axosomatic or axodendritic chemical junction) can be excitatory or inhibitory.
- If an excitatory signal is large enough, an action potential is generated and transmitted by axons to other neurons.
- The BioRC neuron model consists of:
- Dendritic trees comprised of linear voltage adders.
- Excitatory and inhibitory synapses which mimic changes in cell membrane potential due to neurotransmitters and ion-channels.
- Axon hillocks produce action potentials in response to large potential changes.

Challenges and Hypothesis

Challenges:
- Types of synapse (inhibitory or excitatory)
- Reciprocal Inhibition
- Propagation of the signal
- Repeating Signal

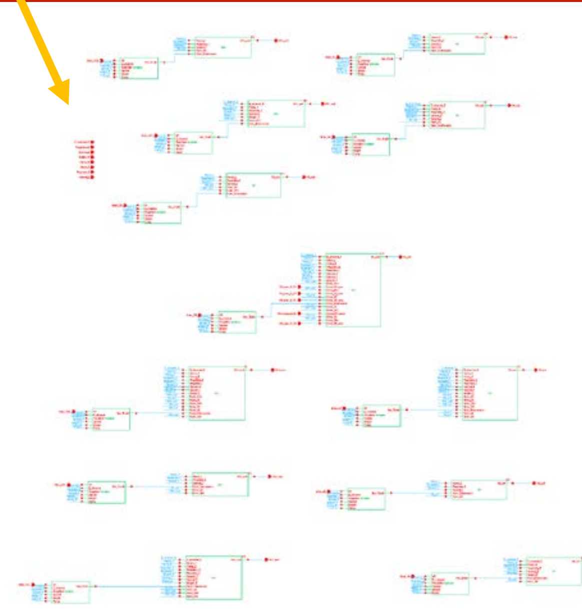
Hypothesis:
- We assumed the type of synapse based on two properties, the network's property of reciprocal inhibition i.e. ventral should inhibit dorsal and vice versa, as well as the property that A and B motor neurons shouldn't excite each other.
- An assumption was made that interneurons are handling propagation of signal. In order to model this behavior long axons were constructed out of RC networks that handle delay and attenuation of signal as it moves down the body.
- Although a CPG (Central Pattern Generator) has not been discovered in C. Elegans, one was constructed out of two axon terminals and some RC delay units to handle just rhythm generation.



Rhythm Generator Schematic

Schematics

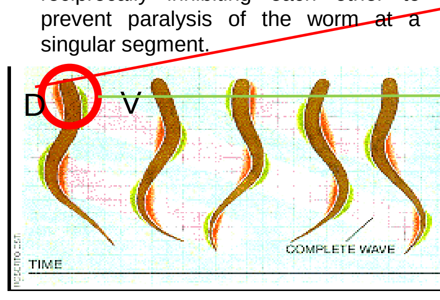
The complete C. Elegans Schematic

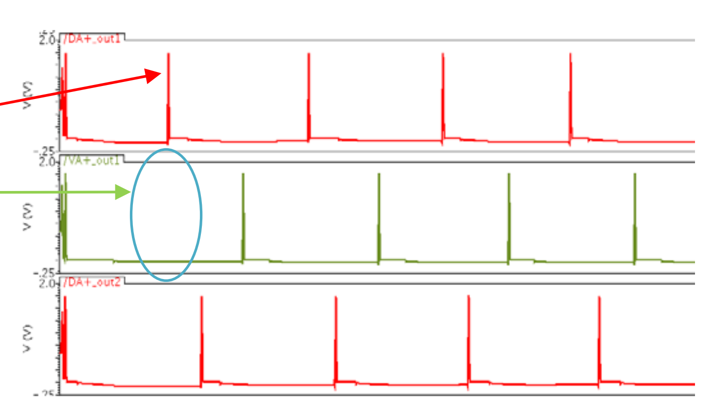


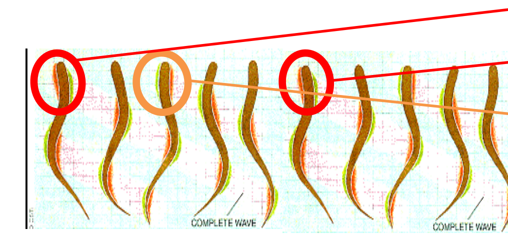
Single Stage (Segment) Schematic

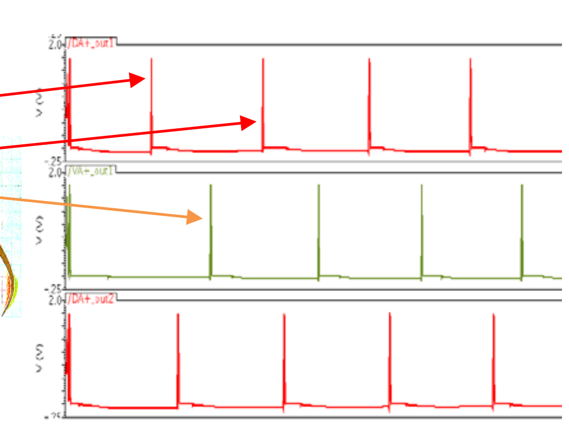
Simulations and Results

Dorsal and Ventral muscles are reciprocally inhibiting each other to prevent paralysis of the worm at a singular segment.



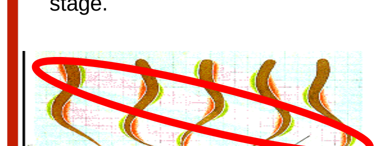


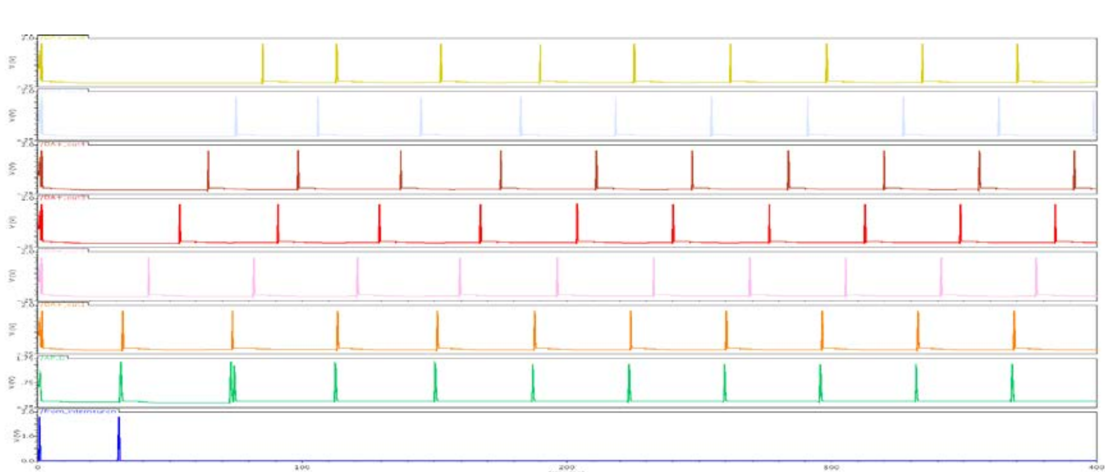




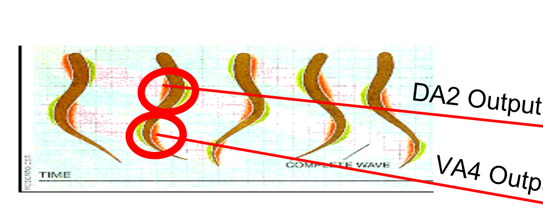
Same Dorsal muscle is spiking after one complete period of wave across the worm body. The Ventral muscle at the same position is spiking in between the two Dorsal spikes.

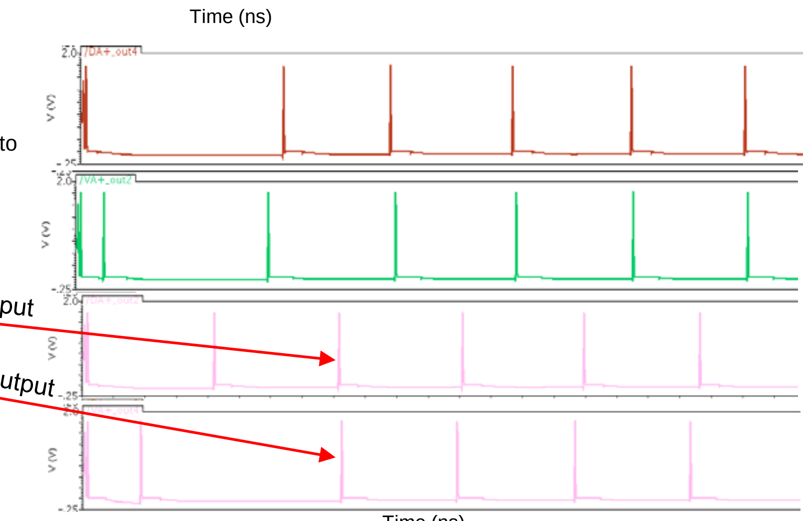
The spike is propagating across the body (dorsal side is shown) with a time delay between each stage.





The 2nd dorsal muscle and 4th ventral muscle (from the head) are spiking at the same time to give the body an S-shape.





Conclusion, Future Work and References

Conclusion:
- The simulation results show that the analog worm is successfully showing touch induced undulatory motion similar to that of C. elegans.
- A model has been developed that takes into account mutual inhibition and resistive properties of the axon for signal propagation.

Future Scope:
- Signal propagation across the worm body may be the result of various factors. We have taken into account just one of them.
- A network can be looked for in the connectome producing oscillations to replace the artificial rhythm generator presently used.
- Once the full connectome is mapped, these issues can be better understood.

References:
[1] Gal Haspel and Michael J. O'Donovan(2011). A Perimotor Framework Reveals Functional Segmentation in the Motoneuronal Network Controlling Locomotion in Caenorhabditis elegans. The Journal of Neuroscience, October 12, 2011 • 31(41):14611–14623
[2] Julijana Gjorgjieva, David Biron, and gal Haspel. Neurobiology of Caenorhabditis elegans Locomotion: Where Do We Stand? BioScience Advance Access, May 7, 2014
[3] Gal Haspel & Michael J. O'Donovan (2012) A connectivity model for the locomotor network of Caenorhabditis elegans, Worm, 1:2, 125-128, DOI: 10.4161/worm.19392
[4] Sukanya Patil, Kaidi Zhou, Alice C. Parker(2015) Neural Circuits for Touch-Induced Locomotion in Caenorhabditis Elegans. Neural Networks (IJCNN), 2015 International Joint Conference on, 12-17 July 2015
[5] http://wormweb.org/
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