# AN ARTIFICIAL MODEL FOR BIOLOGICAL COMPUTATION AND CONTROL FOR A LOCOMOTION SYSTEM

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## ABSTRACT

Each discipline has its own methods of modeling its components and developing the mathematical analysis of the systems which they want to describe. Investigating these systems from different perspectives can provide a means of discovering system operation. Specifically, when approaching the reverse engineering of a biological system, the best description of the elements should include the biological parameters and their known relationships. The modeling should be carefully tied to the biological experimental data and the results of the simulations should provide outputs comparable with actual output data from the original system. Once the model has been thoroughly tested, the mathematical description of the model can be redefined with new variables of interest for the discipline involved. This paper describes the design of a neural network capable of providing simulated output comparable to the deafferented flight neural control behavior of the locust, using GENESIS (General Neural Simulation System). [1]

## 1. INTRODUCTION

The specific locomotion of flight in a locust involves the alternation of the elevator and depressor muscles which control the flapping of the two sets of wings (forewings and hindwings). This alternation is found to be present in the deafferented insect, one without any sensory or central input. Therefore, it is believed that there is a group of local neurons which comprise their own control system to provide just the alternating control of the muscles regardless of any external influences, a Central Rhythm Generator (CRG). This paper discusses a biologically-realistic model developed to provide this control system based upon the actual neurons in the locust. Information from the many experimentalists who have probed this insect for over 40 years provides morphological, physiological, and biological details about the neurons and their connections [2][3] which determines many of the parameters of the elements in the model. The model is designed to provide many of the same characteristics in its output patterns that are inherent in the actual locust flight neuronal patterns as seen in Fig.1. The model for this system is a distributed controller for both sets of wings which is based upon 2 separate three-neuron inhibitory loops which provide a very stable alternating control for the antagonistic muscles involved. The control analysis of the model from an engineering perspective leads to a better understanding of the neural structure of this invertebrate's motor system, and may provide insight into other invertebrate and vertebrate systems.

## 2. DEFINITION OF THE CHARACTERISTICS AND PARAMETERS FOR THE MODEL NEURONS AND THEIR CONNECTIONS

The compartment model of the neurons is based upon their biological parameters which include a soma compartment with membrane resistance and capacitance and resting potential, a dendritic compartment with the synaptic input currents associated with other neurons, as well as any bias currents from hormonal inputs, and an axon compartment with a thresholding function which integrates the inputs and fires an action potential. A schematic of the compartment model with a description of the variables as well as its equations are depicted in Fig. 2 .

## 3. DESIGN OF THE MODEL FOR THE CENTRAL RHYTHM GENERATOR (CRG) FOR FLIGHT LOCOMOTION IN A LOCUST

Using GENESIS, each actual neuron from the locust ganglia involved in the deafferented flight (without sensory input) is described with the characteristics and parameters seen in Fig. 2. A figure for the model connection scheme developed for these central rhythm generation interneurons and the premotor neurons involved in the alternating drive to the elevator motoneuron and depressor motoneuron pools for flight locomotion in the locust is shown in Fig 3. The parameters for the weights of the connections were initially set from data from many invertebrate studies. These weights were then changed to provide a design so that the model output pattern matched that of the actual cell in the network.

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Table I provides the weights for the two CRG neurons, program listings document the weights of all of the neurons.

## 4. COMPARISONS OF SIMULATION OUTPUT TO ACTUAL OUTPUT PATTERNS

The model's output characteristics were checked against some of the overall characteristics which have been noted by experimentalists in deafferented studies of the locust. The rhythm is driven by a recurrent cyclical inhibitory connection between interneurons IN301-IN511-IN501 which constrains both the premotor interneurons and motoneurons to maintaining alternating phases for the depressor and elevator muscles. Fig. 4 shows the simulation output from GENESIS for these three neurons and this can be compared to the experimentatists' data as seen in Fig. 1. The model's rhythm matches the actual deafferented rhythm of 11 Hz which is slower than that found in the intact flying insect (whose normal wingbeat frequency is 20 Hz). According to Wilson and Waldron [4], the burst repetition rate (burst frequency) of each interneuron only varies up to a factor of two (with a maximum for an individual interneuron found to be 200Hz). This seems to be a characteristic of the summation process of the synaptic inputs and this checks against what is observed in the model. The tight linking of the elevator to depressor activity versus the delay and variability of time between depressor to elevator cycle can also be seen in the spike output plot of IN301, IN501, and IN511 in Fig. 4. This is typical of flight cycles found in locusts without sensory control.

## 5. CONCLUSIONS

To be able to answer some of the physiological questions posed by the experimentalists, different hypotheses of neuronal control of flight locomotion in the locust were tested in the modeling process. The results of the design of the final model show that a synaptic network consisting of a stable three-neuron inhibitory loop can provide the basis of alternating control or central rhythm generation for the two sets of outputs to control the forewing and hindwing on one side. The other side is controlled by an identical "distributed" controller synchronized by the same initiating input (a hormonal input due to wind on the antennae in the actual insect), and coordinated by sensory feedback from the other side. One of the advantages of the design of this model versus an Artificial Neural Network model, is that this network connection scheme and its model neurons are based upon those of the actual insect. This provides a means to determine the inherent control mechanisms, and the delineation of each neuron's contribution to that control.

## 6. REFERENCES

[1] Bower, J. and Beeman, D., editors. *The Book of GENESIS, Exploring realistic neural models with the General Neural Simulation System.* Springer-Verlag, Santa Clara, California, 1995.

[2] Wilson, D.M. The flight control system of the locust. *Scientific America*, 218:83-90, 1968.

[3] Pearson, K.G. "Neuronal Circuits for patterning motor activity in invertebrates" in *Comparative neurobiology: modes of communication in the nervous system.* ( F. Strumwasser and M. Cohen, editors) Wiley & Sons, Inc. pp 225-244, 1985.

[4] Wilson, D.M. and Waldron, I. Models for the generation of the motor output pattern in flying locusts. *Proceedings of the IEEE*, 56:1058-1064, 1965.

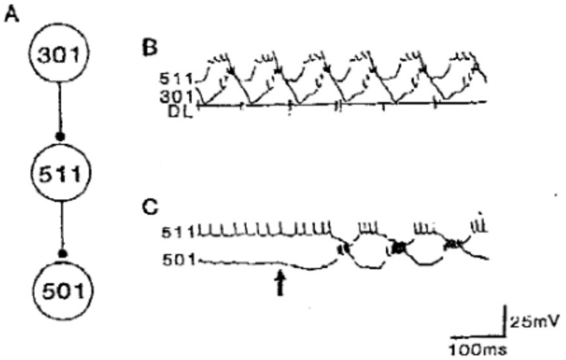
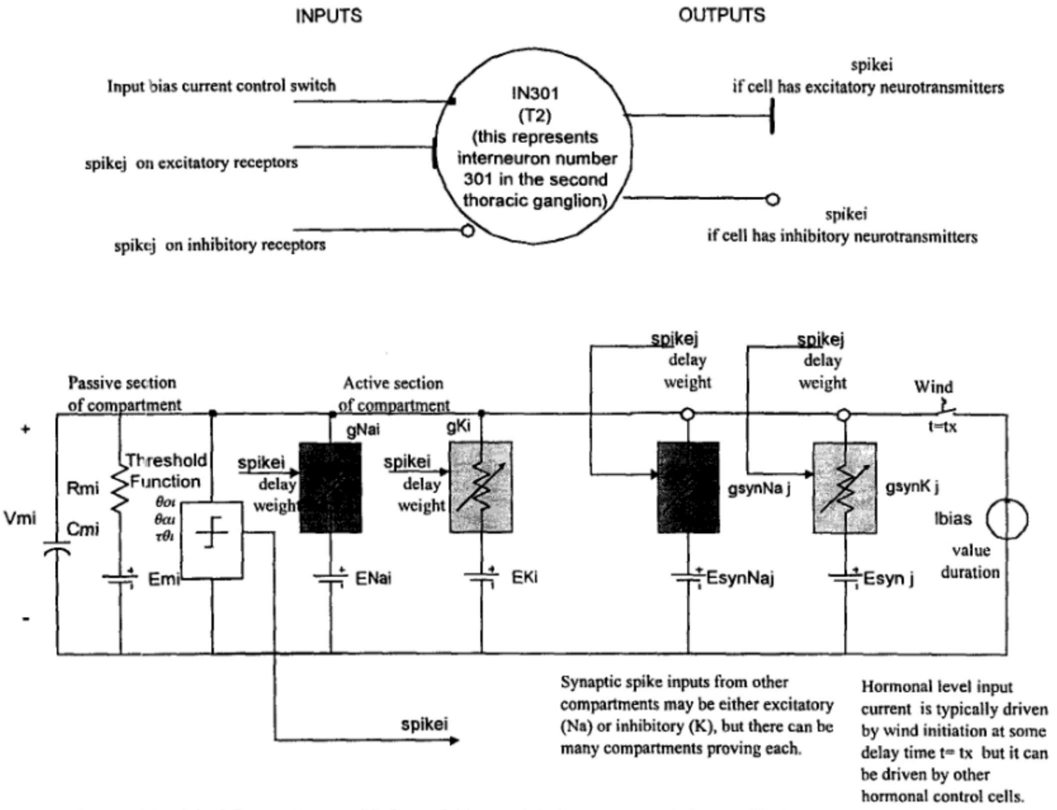


**Figure 1**. Actual rhythmic output patterns from the CRG interneurons in the thoracic region of the locust.
[ Robertson, R. M. "Central neuronal interactions in the flight system of a locust" in *Insect Locomotion* edited by M. Gewecke and Wendler) p.183, 1985]

Typical Neuronal Compartment Symbol and types of Connections it recieves



Internal Model of Compartment with the variables and their parameters to be specified

$$C_m \frac{d}{dt} V_m(t) = I_{bias}(t) - I_{leak}(V_m) - I_{syn}(V_m,t) - I_{act}(V_m,t)$$

$$I_{leak} = (V_m - E_m) g_m \qquad g_m = \frac{1}{R_m}$$

$$I_{syn} = g_{synmax} * g_{syn}(t) * (V_m - E_{syn})$$

$$I_{act} = g_{actmax} * g_{act}(t) * (V_m - E_{act})$$

$$g_x(t) = \frac{A}{(\tau_1 - \tau_2)} \left(e^{-t/\tau_1} - e^{-t/\tau_2}\right)$$

$$\theta(t) = \theta_\infty + (\theta_o - \theta_\infty) e^{(t_x - t)/\tau_\theta}$$

**Figure 2.** This figure shows the neuronal compartment model and the variables and equations, which are used to model the interneurons of the flight locomotion ganglia of a locust.

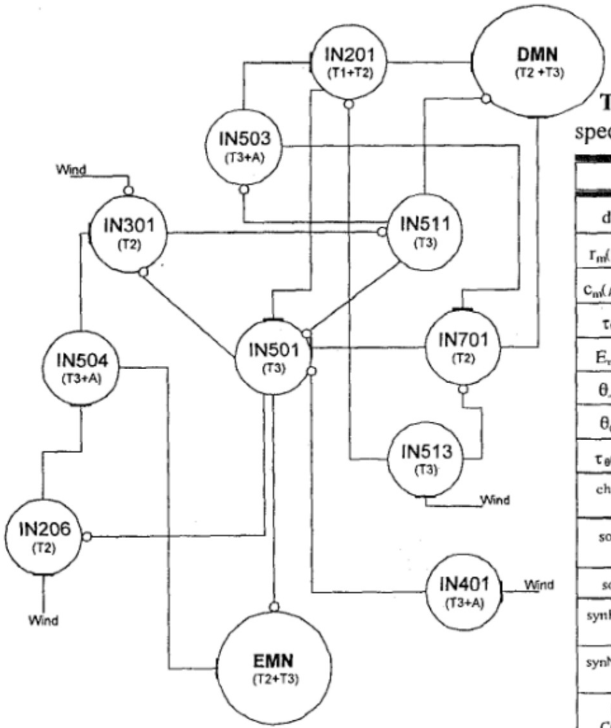


**Figure 3**. Connection model of the neuronal compartments involved in central rhythm generation (CRG) for alternating drives to the elevator motoneurons (EMN) and depressor motoneuron (DMN) pools.

**Table I**. This table shows the initial parameters specifying the neurons in Fig 3.

| | IN301 | | | | | IN501 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| d (μm) | 40 | | | | | 30 | | | | |
| $r_m$(Ω·cm²) | 33k | → | $R_m$=6.565e5 kΩ | | | 33k | → | $R_m$=1.16e6 kΩ | | |
| $c_m$(μF·cm⁻²) | 1 | → | $C_m$=5.027e-5 μF | | | 1 | → | $C_m$=2.83e-5 μF | | |
| τ(msec) | 32.8 | | | | | 32.8 | | | | |
| $E_m$(mV) | -58 | | | | | -58 | | | | |
| $\theta_\infty$(mV) | -48 | | | | | -48 | | | | |
| $\theta_d$(mV) | 0 | | | | | 0 | | | | |
| $\tau_\theta$(msec) | 5 | | | | | 5 | | | | |
| channels | gsyn (S) | $\tau_1$ (ms) | $\tau_2$ (ms) | Esyn (mV) | delay (ms) | gsyn (mS) | $\tau_1$ (ms) | $\tau_2$ (ms) | Esyn (mV) | delay (ms) |
| somaNa | 1.7 e-5 | 1 | 1 | 10 | 0 | 1.7 e-5 | 1 | 1 | 10 | 0 |
| somaK | 2e-5 | 3 | 3 | -80 | 0 | 2e-5 | 3 | 3 | -80 | 0 |
| synK (501) | 2.7 e-5 | 10 | 10 | -80 | 1.5 | | | | | |
| synNa (301) | | | | | | 2.5 e-5 | 10 | 10 | 10 | 8 |
| Bias Current | 0.2nA | | | | | 0 | | | | |

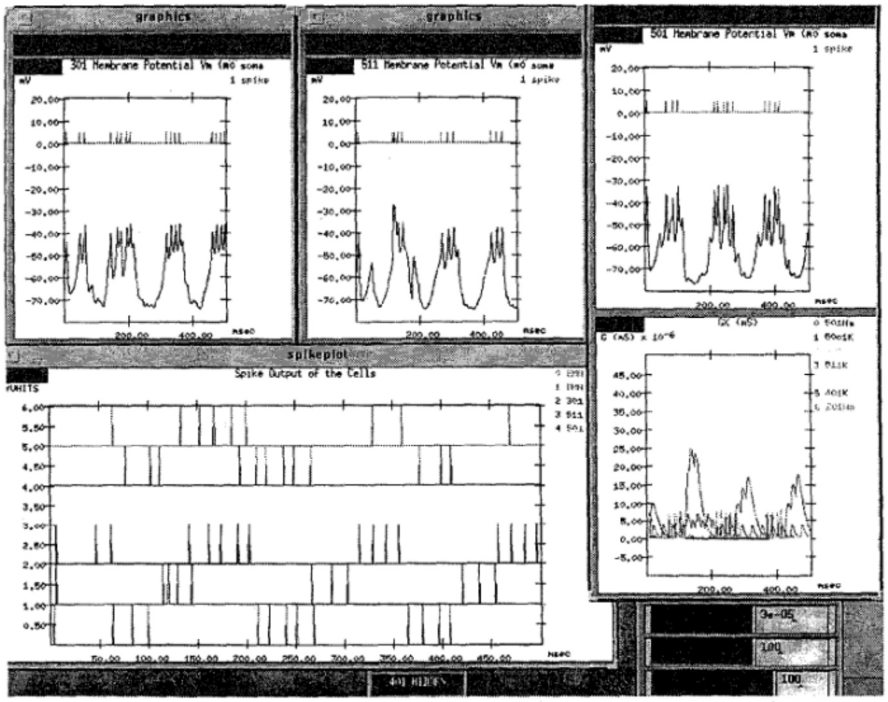


**Figure 4**. GENESIS simulation of the deafferented flight model showing the main CRG patterns of IN301, IN501, IN511.