Bio-inspired models of astrocyte-neuron interactions for fault tolerant neuro-control systems.

David Halliday[1], Anju Johnson[1], Alan Millard[1], Junxiu Liu[2], Shvan Karim[2], Jim Harkin[2], Jon Timmis[1], Andy Tyrrell[1], Liam McDaid[2]

[1]University of York, Electronic Engineering, York, United Kingdom. [2]Ulster University, School of Computing and Intelligent Systems, Derry, United Kingdom

INTRODUCTION & BACKGROUND

- The human brain exhibits many desirable properties in the context of engineering systems.
- One property is fault tolerance, the ability to maintain stable function during and after periods of disease or injury.
- Recent work has highlighted the role of astrocytes in regulating neuronal function.
- We exploit computational models of retrograde signalling in astrocytes as a principle for developing fault tolerant electronic systems.

MODEL OVERVIEW

- System uses biologically inspired spiking astrocyte neural network (SANN) and learning rule.
- Learning rule combines Bienenstock, Cooper and Munro (BCM) rule with Spike Time Dependent Plasticity (STDP) rule to create novel BSTDP rule.
- SANN uses coupling between tripartite synapses and γ-GABAergic (GABA) interneuron.
- BSTDP rule modulates height of learning window in asymmetric Hebbian learning process.
- Interactions with GABA interneuron act to band-pass filter and route spike trains according to firing frequencies.

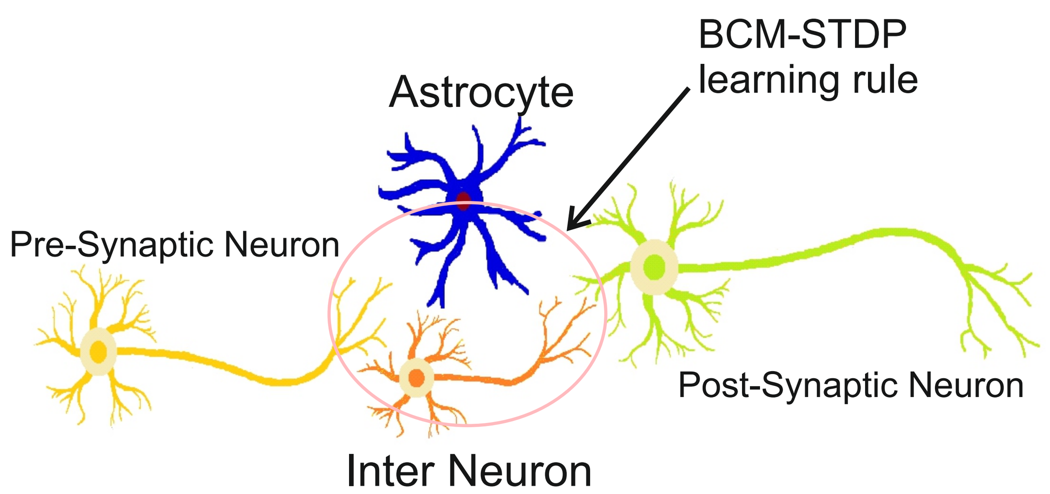


Figure 1. Schematic of SANN with BSTDP learning rule.

Combined BCM-STDP (BSTDP) rule captures interactions between Astrocyte, GABA interneuron and pre- and post-synaptic neurons (pink circle).

These interactions allow SANN to:
1. Continuously route information to different areas of the SANN according to spike train firing rate.
2. Initiate self-repair in the presence of synaptic failures.

MODEL DETAILS

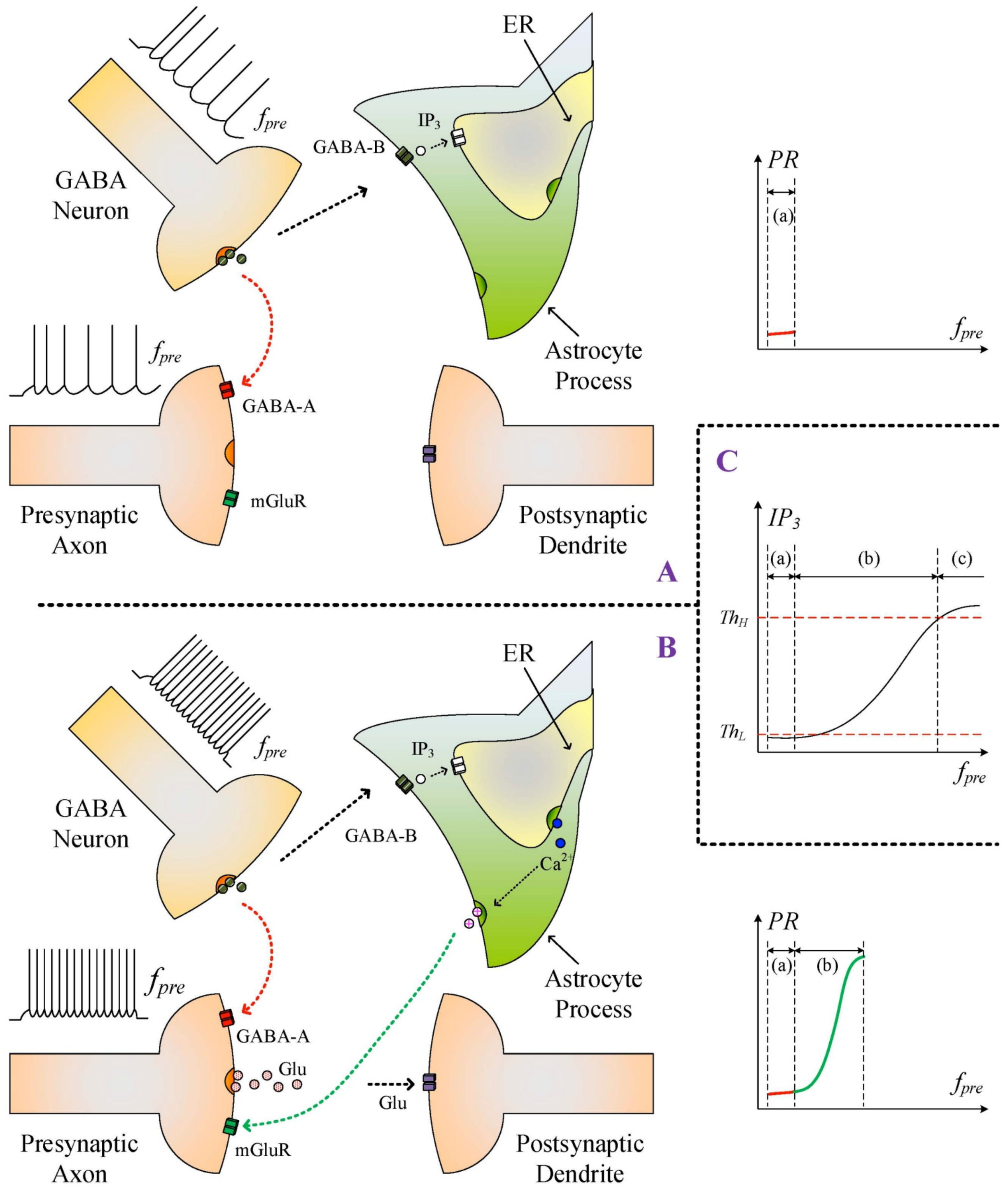


Figure 2. Details of SANN-BSTDP model.

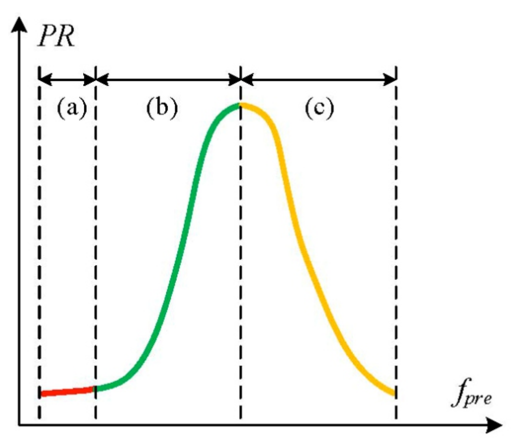
(A) At low pre-synaptic firing frequencies, f_{pre}, GABA interneuron inhibits pre-synaptic neuron (red arrow), and causes inositol 1, 4, 5-triphosphate (IP_3) release in astrocyte (black arrow). The IP_3 release is insufficient to trigger a Ca^{++} response. Overall probability of release (PR) between pre-synaptic and post-synaptic neuron remains low due to GABA-A inhibition (inset, red line).

(B) As pre-synaptic firing rate, f_{pre}, increases, levels of IP_3 increase and exceed the lower threshold, Th_L, for Ca^{++} release. This causes Calcium induced glutamate release from the astrocyte which binds to metabotropic glutamate receptors, mGLuR (green arrow) overcoming the inhibitory effects of GABA-A (red arrow). This results in an increase in PR (inset, green line).

(C) Continued increase in pre-synaptic firing rate, f_{pre}, results in levels of IP_3 within the astrocyte crossing the upper threshold, Th_H, for oscillatory Ca^{++} response which ceases, causing the GABA-A inhibition from the interneuron to dominate and reducing PR.

The overall effect is to generate a Gaussian tuning curve for PR as a function of f_{pre} : $PR = \frac{(f_{pre} - f_s)}{2\sigma^2}$
where f_s, is the sensitivity, or centre, frequency and σ the width of tuning curve.
Both these parameters can be adjusted to determine the coding scheme used by the network, see figure 3.

Figure 3.
Tuning of PR as a function of pre-synaptic firing rate.



SANN Fault Tolerant Neuro-Control System

- SANN was implemented on Artix-7 FPGA development board.
- Used to control autonomous mobile robot performing simultaneous target-following and obstacle avoidance.

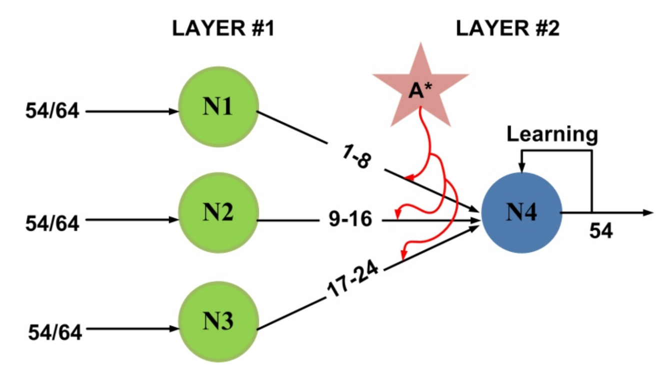


Figure 4. Building-block for SANN fault-tolerant learning.
- Each synaptic connection has 8 parallel pathways.
- Input layer neurons (N1, N2, N3) receive signals at rate of 54 or 64 spikes/window, coding binary values 0 or 1.
- Astrocyte A* filters frequencies arriving at neuron N4, selecting only a pre-determined subset of inputs.
- For this specific pattern, system learns to produce the required output spike rate of 54 spikes/window.

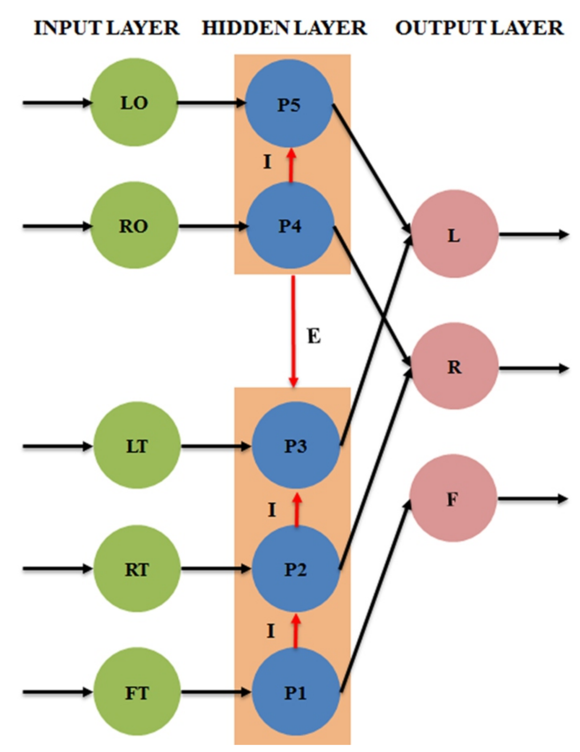
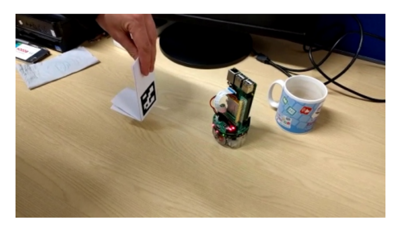


Figure 5. SANN for self-repairing robot neuro-controller.
- Neurons LO and RO receive signals when the robot detects an obstacle to its left or right, respectively.
- Neurons LT, RT, and FT receive signals when the robot detects the target to its left, right, or front, respectively.
- Astrocytes (not shown) control the specific patterns of inputs delivered to hidden layer neurons P1 - P5.
- I and E are control signals used to prioritise direction of movement. The resulting outputs of the neurons in the output layer are used to move the robot in left, right, or forward direction (L, R, F).

Please see videos during presentation session.

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