Associative Processing using Coupled Oscillators

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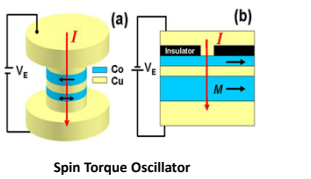
Motivation

- Compete and complement "end of life" CMOS for low power high density applications
- Exploit non-charge based state variables and non-Boolean operations
- Explore systems based on new devices for compute intensive tasks such as pattern recognition and computer vision

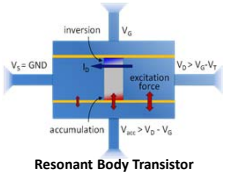
Goals

- Implement associative memory using coupled oscillator network
- Represent states by frequency/phase relationship between oscillators.
- Abstract distance metric and degree of match for pattern matching
- Apply model on problems of pattern recognition and image processing

Nonlinear Nano-Oscillator Cluster

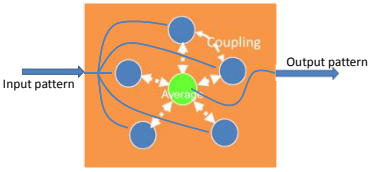


Spin Torque Oscillator

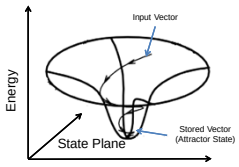


Resonant Body Transistor

Two types of Nano-Oscillators: STO, RBO. (Rippard. 1995, Weinstain 2010).



Coupled Oscillators



Attractor Basin

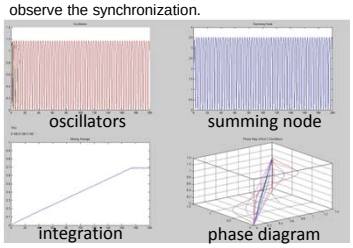
Use the synchronization of coupled non-linear oscillators to perform a pattern matching operation. This is a dynamic system that can evolve from an unstable initial state to a stable state which is a local minimum of an energy function (attractor basin), similar to a Hopfield neural network.

Model the coupled oscillator cluster using the Belousov-Zhabotinsky reaction model (Asai et al. 2004). This non-linear oscillator model can be implemented in hardware with two op-amps in a feedback loop. Simulate a cluster of coupled oscillators using these equations in Matlab and observe the synchronization.

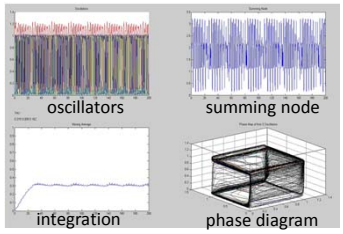
$$\frac{d[x_{i1}]}{dt} = \frac{1}{\tau}\left(-[x_{i1}] + f([x_{i1}] - [x_{i2}], \beta_1)\right) + C \cdot \sum_{i=1}^{N} x_{i1}$$

$$\frac{d[x_{i2}]}{dt} = -[x_{i2}] + f([x_{i1}] - \theta, \beta_1)$$

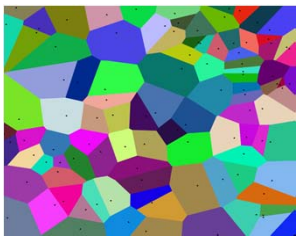
Where $f(x, \beta) = \frac{1+\tanh \beta x}{2}$



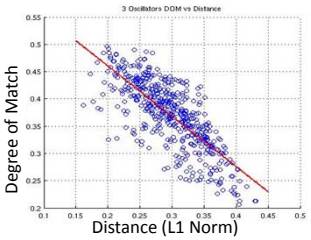
Simulation of a 3-oscillator cluster, input vector (1,1,1), a good match



Simulation of a 3-oscillator cluster, input vector (0.2,0.09,1.6), a bad match

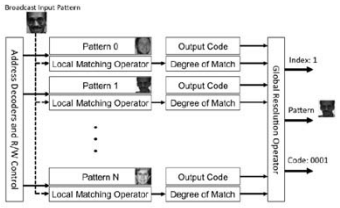


High dimension vector space is tessellated by multiple attractor basins. The area of each region is determined by the distance metric that is abstracted from the energy function.

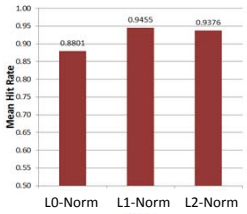


Degree of Match (DoM) defined by amplitude of lowest frequency component in coupled oscillation. DoM vs. L1 (Manhattan) distance, 500 runs. Max residual: 0.1334, square sum of residuals: 0.7616

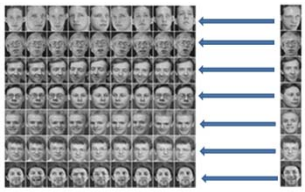
Application: Facial Recognition Problem



Associative Memory Model for Facial Recognition

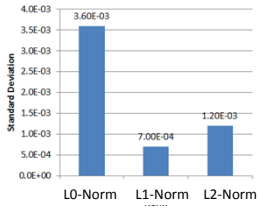


Mean Hit Rates for Recognition by Different Norms



Training/Clustering Data Test Data

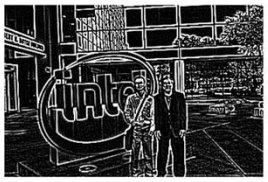
Cross-validation Test: retrieve the nearest neighbor to an input photograph.



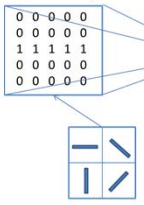
Standard. deviation of Hit Rates

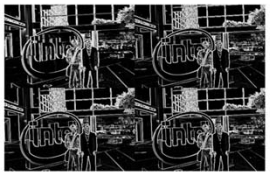
Application: Edge Detection for Image Processing

$$s = \sum_{i=1}^{8} p_{center} - p_i$$



For salience detection, the salience of each pixel is the sum of the results of subtraction between the center pixel and pixels around it . The detected edges are obtained by displaying the salience of all pixels as an image.





For feature extraction, mask four filters on to a piece of image and shift it as a 2-D convolution operation. Then take the difference between original pixel and the '1's bar mask as the input vector to the oscillator cluster. The results are four edge detected images with different angles in texture. This operation could also be used in a hierarchical convolutional neural network.

Summary: In this project, we explore the behavior of non-linear oscillator clusters and the associative processing model that performs the nearest neighbor search by using the synchronization of coupled oscillators. Application cases include recognition of human faces and feature extraction for image processing.

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