Pattern Matching Using Coupled Oscillators

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Background

To overcome the power and performance limitations of CMOS technology, researchers are developing new technologies that are not based on a charge-based representation of state. In this work, we introduce a network of weakly coupled oscillators to perform the cognitive task of pattern recognition. We use a CMOS ring oscillator to study the behavior of the system, treating the ring oscillator as an analog for a class of emerging technologies that includes spin torque oscillators, Belousov–Zhabotinsky, or resonant body transistors. All circuits were simulated using the Cadence Virtuoso Analog Design Environment.

I. Pattern Matching

We compare two vectors, whose pairwise difference is represented by \( v = |v_1, v_2, v_3, ..., v_{N-1}| \) and offset by \( v_{\text{match}} \). If all elements of \( v \) are equal to \( v_{\text{match}} \), we have a perfect match.

II. Oscillator System

- Inverter ring produces a frequency non-linearly dependent on its input voltage, \( v_i \) [Fig. 1 & 2]
- Common node, \( v_{\text{com}} \), resistively couples \( N \) oscillators [Fig. 3]
- Oscillators at same frequency lock in phase [Fig.4]
- CMOS inverter buffers voltage at \( v_{\text{ctrl}} \)
- Rectification and integration produces steady state voltage [Fig. 5]

\[
\text{V(t)} = \frac{2}{N(N+1)} \left( \sum_{i=1}^{N-1} \sum_{j=1}^{i-1} \exp \left( -\frac{|v_i - v_j|^2}{\delta} \right) + \alpha \sum_{i=1}^{N-1} \exp \left( -\frac{|v_{\text{match}} - v_i|^2}{\gamma} \right) \right)^{\frac{1}{2}}
\]

Eq. 1 - Curve Fit Equation for Steady State Oscillator Behavior

III. Steady State Response

- Resonance causes increased values of \( v_{\text{out}} \) [Fig. 5 & 6]
- Detector shows maximum when elements of input vector are all equal
- Different input vectors produce family of curves shown above [Fig. 7]
- Cases where \( v_j = v_i \) produce overall higher voltages and only have a single peak corresponding to \( v_{\text{out}} = v_j \)
- Cases where \( v_j \neq v_i \) produce two peaks where \( v_{\text{out}} = v_j \) and where \( v_{\text{out}} = v_j \)
- System reports perfect match when all \( v_i \) are equal, even for \( v_j \neq v_{\text{match}} \)

IV. Control Oscillator

- ‘Control’ oscillator coupled into \( v_{\text{out}} \) to increase perfect match output, ensuring that it is a global maxima [Fig. 8]
- Constant input voltage \( v_{\text{ctrl}} \) given to control oscillator
- Control oscillator coupled via \( R_{\text{ctrl}} \) whose value can be lowered to increase the weighting of the control oscillator
- Lower \( R_{\text{ctrl}} \) values raise the curve corresponding to a perfect match
- For \( N = 3, R_{\text{ctrl}} = 50k\Omega \)
- \( R_{\text{ctrl}} \) decreased to 30k\Omega for \( N = 5 \) [Fig. 9]

V. Mathematical Model

- Curve fit equation, \( w_{\text{out}} \), allows for integration of oscillator behavior into a higher level architecture [Eq. 1, Fig. 10]
- Pairwise differences between \( v_i \) and \( v_j \) are more important than the actual values of \( v_i \) and \( v_j \)
- Peaks occur when pairwise differences between different elements of \( v \) are zero
- Peaks modeled by Gaussian curves
- Parameter \( \gamma \) describes the width of the peaks
- \( \alpha \) equals 50k\Omega/\( R_{\text{ctrl}} \) to account for the weighting of control oscillator
- Equation is normalized to the number of pairwise differences between each pair of inputs and also \( v_{\text{match}} = N(N+1)/2 \)
- Exponent 1/2 is a curve fit parameter to reduce the height of upper peaks
- Curve fit is linearly related to simulation results [Fig. 11]

Conclusions

We have successfully captured the complex behavior of the pattern matching abilities of the oscillators in a simple analytic equation, we can use this equation in high level (architecture) modeling to support algorithmic development for image processing and pattern recognition tasks. We are currently investigating how well this same function can be used to model the behavior of spin torque oscillators and Belousov–Zhabotinsky oscillators.

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