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 $\mathbf{V} = [v_0, v_1, v_2, ..., v_{N-1}]$ and offset by v_{match}. If all elements of $\mathbf{V}$ are equal to v_{match}, we have a perfect match.

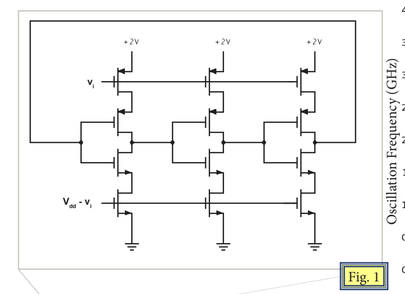


Fig. 1

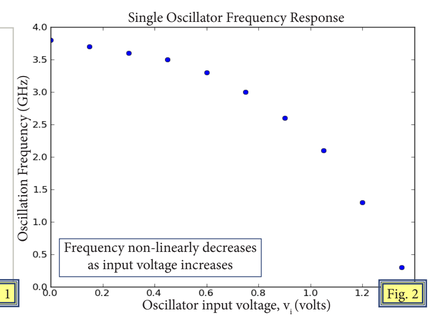


Fig. 2

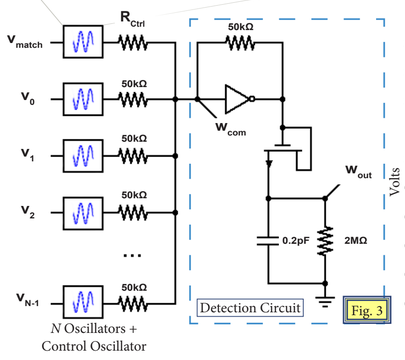


Fig. 3

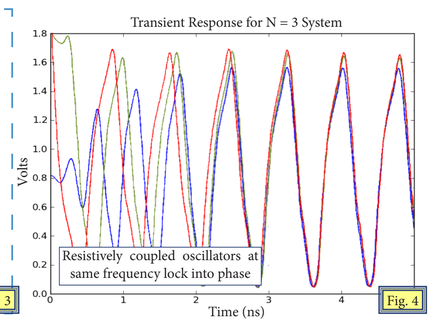
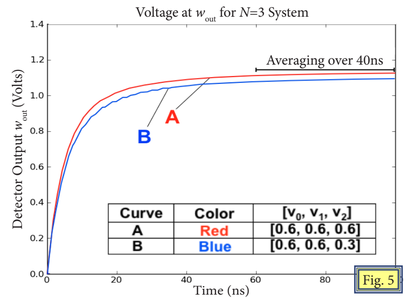


Fig. 4

II. Oscillator System

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



Curve	Color	[v_0, v_1, v_2]
A	Red	[0.6, 0.6, 0.6]
B	Blue	[0.6, 0.6, 0.3]

Fig. 5

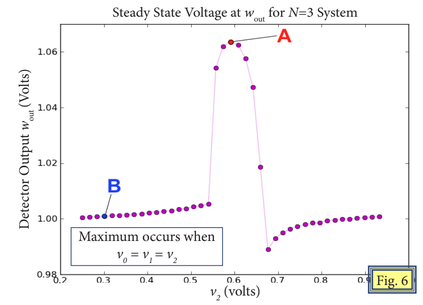


Fig. 6

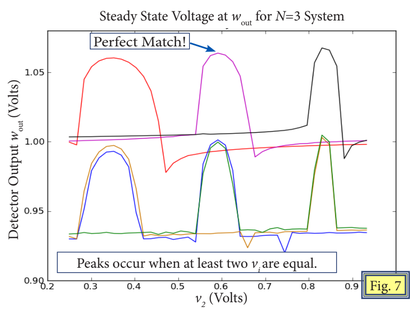


Fig. 7

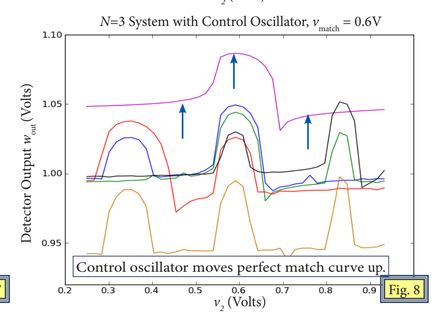


Fig. 8

Color	Red	Blue	Purple	Orange	Green	Black
$[v_0, v_1]$	[0.35, 0.35]	[0.35, 0.6]	[0.6, 0.6]	[0.35, 0.85]	[0.6, 0.85]	[0.85, 0.85]

III. Steady State Response

- Resonance causes increased values of w_{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 $v_0 = v_1$ produce overall higher voltages and only have a single peak corresponding to $v_0 = v_1 = v_2$
- Cases where $v_0 \neq v_1$ produce two peaks where $v_0 = v_2$ and where $v_1 = v_2$
- System reports perfect match when all v_i are equal, even for $v_i \neq v_{match}$.

IV. Control Oscillator

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

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

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

V. Mathematical Model

- Curve fit equation, w_{fit}, 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 $\boldsymbol{V}$ are zero
- Peaks modeled by Gaussian curves
- Parameter γ describes the width of the peaks
- α equals 50kΩ/R_{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_{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]

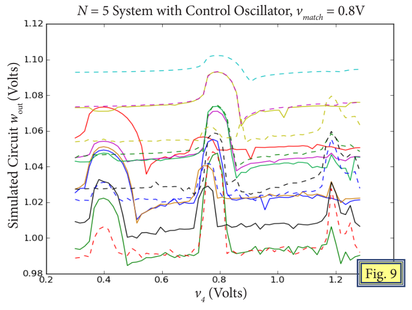


Fig. 9

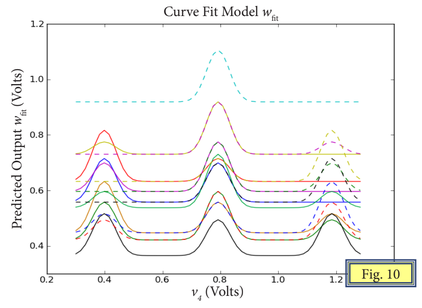


Fig. 10

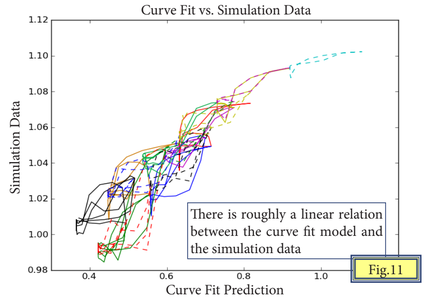


Fig.11

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.

Acknowledgments

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