Pattern recognition with nanoscale oscillators

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Abstract: Spin Torque Nano Oscillators are nanometric devices that turn polarized electrical current into magnetic oscillations via the spin transfer torque effect. These nanometric oscillators present non-linear behavior between amplitude and frequency resulting in synchronization with external perturbations or other oscillators. These properties, as well as the dependency of their characteristic oscillation with the current applied makes them very suitable candidates to be the physical hard-ware for artificial neural networks.

I. INTRODUCTION

In the recent years, Artificial Neural Networks (ANN) have become the algorithm benchmark for artificial intelligence. An ANN consists of a large set of units, called artificial neurons, connected between them. Computation is achieved by transferring information throughout the different layers of neurons. An input signal is given to the system, neurons in the input layer compute a series of non-linear operations to the signal and passes it on to a deeper layer of the network. Further operations transform the signal throughout the hidden layers until it gets to the output layer of neurons, which gives an output signal. This algorithm is extremely useful for pattern recognition tasks as we can create a map of expected outputs given known inputs so when an unknown input is given we can recognize its state just by comparing its output value with the map created beforehand. Nowadays, computation with ANN must be done with simulations, which require a large amount of electrical and computing resources. However, new studies present Spin-Torque Nano-Oscillators (STNOs) as efficient candidates to implement ANN. [2]

STNOs are nanometric devices that turn electrical current into magnetic oscillations. The basic concept of STNO devices can be seen in FIG 1. A nanoscale electrical contact is attached to a multilayered ferromagnetic structure [1]. The multilayer consists of a fixed layer (PL) and a free layer (FL) separated with a non-magnetic material. The free layer is typically made of permalloy ($Ne_{80}Fe_{20}$) or iron (Fe) and between 2-5 nm thick. The fixed layer is also known as polarized layer as its main purpose is to generate a polarized current of electrons. Polarization is achieved with an external magnetic field. This layer is thicker than the free layer and is typically 10-40 nm wide. The purpose of the FL is to generate a spin-wave resonance due to the interaction with the polarized current of electrons (spin transfer torque). These two layers are separated by a non-magnetic material in order to avoid any magnetic interaction between the states of the two layers. [1][3][4]

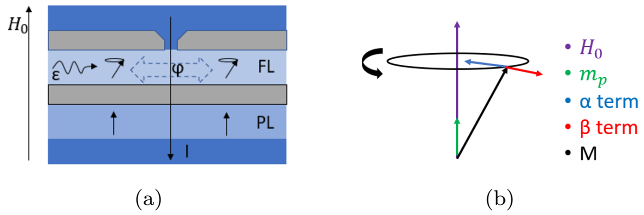

FIG. 1: Representation of an STNO (a) and the different terms of the Landau-Lifshitz-Gilbert equation for the precession of the magnetization (b). ε represents the oscillating perturbation of the input data and φ the interaction between oscillators.

II. MATHEMATICAL MODEL

In order to simulate the STNOs we used the Landau-Lifshitz-Gilbert equation in thin ferromagnetic films[1]. This equation models the dynamics of a magnetization vector $\vec{M}$ in an external magnetic field, $\vec{H}_{\text{eff}}$. If an external field is applied, the spin-magnetic moments will begin to precess around the direction of the applied field. The magnetic moment will eventually align with the external field due to damping effects. However, if a polarized current is applied to the magnetic moment a positive damping factor will appear, which will lead us to stable oscillations of the magnetic moment. This phenomena is described by the following expression:

$$\frac{\partial \vec{M}}{\partial t} = -|\gamma|\mu_0 \vec{M} \times \vec{H}_{\text{eff}} - \alpha \frac{|\gamma|\mu_0}{M_{\text{s}}} \vec{M} \times \vec{M} \times \vec{H}_{\text{eff}} + \beta \vec{M} \times \vec{M} \times \vec{m}_{\text{p}}, \quad (1)$$

where γ is the electron gyromagnetic factor, μ_0 is the permeability of empty space and M_s is the saturation magnetization. A visual representation of the precession of the magnetization as well as the different terms of Equation 1 is illustrated in FIG. 1. We can identify that the precession (first) term and the damping (second) term are moderated by the effective field $\vec{H}_{\text{eff}}$ which is a sum

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Material	M_s (T)	ω_L (GHz)
Fe	2.14	60
$Ni_{80}Fe_{20}$	1.05	29.43
Fe_3O_4	0.6	16.82

TABLE I: Saturation magnetization and Larmor frequency of typical materials used for STNOs

of the applied field, demagnetizing field and the exchange field, proportional to $\nabla^2\vec{M}$. However, in the situations studied, the exchange field term is negligible as we can consider the variations of $\vec{M}$ uniform due to the size of the STNO. Besides, we will keep adding terms as we develop our simulation. So, for an isolated spin-magnetic moment in a external magnetic field the effective field remains as follows:

$$\vec{H}_{\mathrm{eff}} = (H_0 - M_z)\hat{z}, \tag{2}$$

note that we have defined the direction of the applied field to the z axis. This will remain throughout the study. In order to obtain general and more intuitive results we normalize the equation (1). Henceforth, we define the following dimensionless parameters:

$$\vec{m} = \frac{\vec{M}}{M_s} = (m_x, m_y, m_z); \quad \tau = \frac{\omega_L}{2\pi}t; \qquad \vec{h}_{\mathrm{eff}} = \frac{\vec{H}_{\mathrm{eff}}}{M_s}, \tag{3}$$

where $\omega_L = 2\pi\gamma\mu_0 M_s$ is the Larmor frequency for an applied field M_s. Further note that every single parameter is described by M_s, so if we choose a value for the saturation magnetization the experiment would be fully determined. Typical values for M_s are given in the table I. We can see how a large range of typical frequencies can be achieved. Take into account that iron is the material with the highest known value for M_s so we won't have Larmor frequencies larger than 60 GHz. However, lower frequencies can be achieved just by diluting the ferromagnet. After the normalization we end up with the following equation:

$$\frac{d\vec{m}}{d\tau} = -\vec{m}\times\vec{h}_{\mathrm{eff}} - \alpha\vec{m}\times\vec{m}\times\vec{h}_{\mathrm{eff}} + \beta\vec{m}\times\vec{m}\times\vec{m}_p, \tag{4}$$

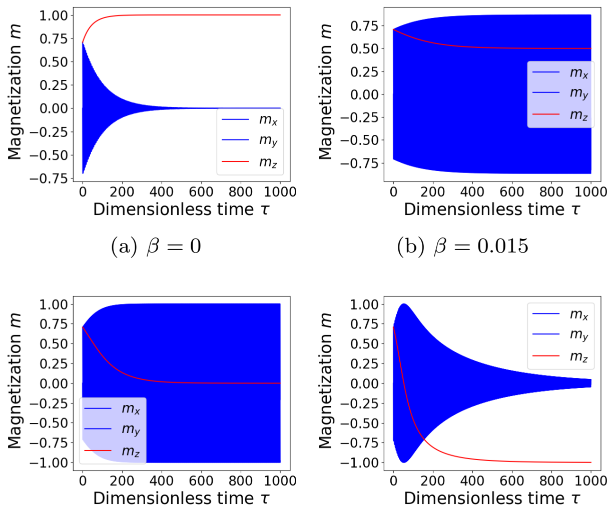
further note that, as we normalized the magnetization, only two coordinates are needed to complete the simulation as the third one is restricted by the following expression:

$$m_z = \sqrt{1 - m_x^2 - m_y^2}, \tag{5}$$

however, this expression is not used in our simulation as for a certain value of β the z component of the magnetization becomes negative. If we take a look at the negative damping term we can see that is characterized by α. This parameter is called *damping constant* and it is a property of each material. Typical values of α for good ferromagntes like iron or cobalt are $\alpha = 0.01$, yet some reports affirm that for new meta-materials this constant can be reduced one or even two orders of magnitude. The damping constant can be greater than one for bad ferromagnets. Theoretically, the smaller the constant the better as wider ranges of frequencies would be achieved.

On the other hand, the positive damping term is only characterized by β as $\vec{m}_p$, due to normalization, is a vector in the z axis equal to one. The parameter β depends on the geometry of the STNO and its material, nonetheless, we can express β as a function linearly dependent with the applied polarized current, $\beta = \beta_0 I$.

If the applied current has enough intensity, the spin-torque term can overcome the damping term and can induce an oscillation of the magnetization depending mainly on β and the applied field h. As we will maintain the applied magnetic field constant throughout the simulation, the only factor that is able to change the frequency of oscillation is the applied current, characterized by β.



(a) $\beta = 0$ (b) $\beta = 0.015$ (c) $\beta = 0.020$ (d) $\beta = 0.033$

FIG. 2: Normalized magnetization's x, y and z components over time under a constant magnetic field ($h = 2$) on the z axis. Synchronization over a long period of time is achieved in (b), (c) and (d) whereas in (a) m quickly orientates in the direction of the applied field due to negative damping. In case (d) m_z opposes to the applied field due to the fact that the positive damping term easily overcomes the negative one.

III. SIMULATION

All simulations mentioned below have been simulated solving equation 4 with the Odeint function from Python's Scipy.integrate library. Before analyzing the coupling map of two interacting STNOs with two external frequencies, we will study the dynamics of a STNO under different circumstances. Note that the initial conditions $(m_x, m_y, m_z) = (0, \frac{\sqrt{2}}{2}, \frac{\sqrt{2}}{2})$ are the same in every case studied. The external magnetic field applied is the same in every simulation and always applied along the z axis. We have chosen $h = 2$ as $h > 1$ is mandatory in order to overcome the demagnetizing field caused by the spontaneous magnetization.

A. Isolated STNO

First we will start by simulating an isolated STNO under a constant magnetic field. Results can be seen in FIG 2. As we can see, if no polarized current is applied ($\beta = 0$), the damping factor will align the magnetization in the direction of the applied field. Note how the amplitude of the x and y go from the initial conditions to zero as the z component grows. No stable oscillation is achieved for $\beta < 0.012$, the negative damping term overcomes the positive. We can see how for $\beta = 0.015$ stable oscillations are achieved yet the amplitude of the oscillation is not maximum as $m_z \neq 0$. On the contrary, maximum amplitude oscillations can be seen for $\beta = 0.020$, the negative damping term is compensated by the positive. Note that $m_z = 0$ so the precession describes a circumference on the $z = 0$ plane. For $\beta > 0.035$ the stable oscillation range narrows and m_z quickly turns the negative z axis overcoming the external field, the positive damping term easily overcomes the negative one.

We can get the frequency of the oscillation by analyzing the Fourier Transform of a component perpendicular to the external field.

β	0	0.015	0.020	0.035
Frequency(GHz)	5.33	7	9.36	14

TABLE II: Frequency of oscillation for different polarized currents for a Permalloy STNO ($M_s = 1.05$ T) and external magnetic field $H_0 = 2.1$ T.

From TABLE II we can see that the frequency rises with the current applied. If we take a look at FIG 3 there is a certain range of β ($0.012 < \beta < 0.033$) in which the frequency is linearly dependent with the applied current. Out of this range frequency remains the same regardless the applied current.

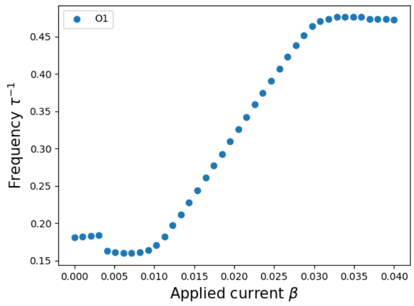


FIG. 3: Frequency of the STNO as a function of the applied current factor β. Frequency of oscillation is linearly dependent with the applied current for $0.012 < \beta < 0.033$. Outside this range the frequency does not depend on β.

B. Coupling with an external frequency

STNOs are non-linear oscillators and have the ability to synchronize with external harmonic electromagnetic perturbations. Different type of data can be parameterized with frequencies, the most obvious one is sound [2], apart from that, shapes and colors can also be represented as frequencies, making STNOs very suitable hardware for image recognition. These input data can be given to the system as an external harmonic magnetic field along the x or y axis with a characteristic frequency of oscillation. We can include these perturbation to our simulation by modifying the effective magnetic field form Equation 2.

$$\vec{h}_{\text{eff}} = (h_0 - m_z)\hat{z} + \sum_i \varepsilon_i \sin(\omega_i \tau)\hat{x}, \qquad (6)$$

where ε_i and ω_i are the amplitude and angular frequency of the i^{th} perturbation. In this project we used two different frequencies to parameterize the input data, although higher dimension maps with more interaction between different oscillators can be achieved. FIG 4 shows that when the external frequency is near the the characteristic frequency of the prcession, the STNO couples with the perturbation oscillating at the same rate for a certain region. The synchronization range can be modified by changing the amplitude of the magnetic perturbation. Moreover, FIG 4 also shows how as the characteristic frequency of oscillations rises, the synchronization range rises with it. Typical values for the external magnetic field perturbation are two orders of magnitude smaller than the main magnetic field applied. This shows how small perturbations can drastically affect an STNO oscillating rate, being this the main drawback of this technology as it can be affected easily by external noise.

C. Interacting STNOs

The precession of an STNO produces a small harmonic magnetic field with the same frequency as the precession of the magnetization. The generated field is weak and banishes quickly with distance, however, as STNOs are nanodevices, several oscillators can be placed close enough that they interact with each other. If we have system with multiple STNOs their oscillation can modify each others precession and synchronize with other STNOs even without an external perturbation. This phenomena is very similar to the one described in section

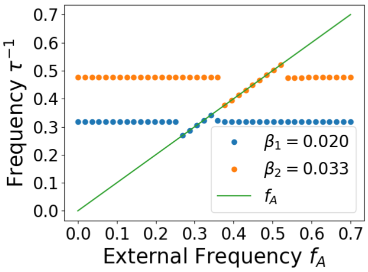
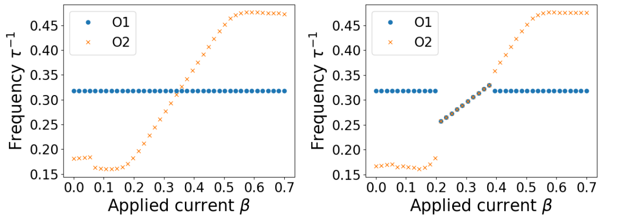


FIG. 4: Frequency of an STNO as a function of an external frequency for different values of β for a magnetic perturbation amplitude of $\varepsilon = 0.05$. Synchronization with the external frequency can be seen for a certain range of frequencies when the external frequency approaches the characteristic frequency of the oscillator. For the same value of the amplitude of the perturbation the synchronization range rises with the characteristic frequency of the oscillator.



(a) $\varphi_{1,2} = 0$ (b) $\varphi_{1,2} = 0.004$

FIG. 5: Frequency of two nano-oscillators as a function the polarized current of one of them with (b) and without (a) interaction. The current applied to the first oscillator (O1) is $\beta = 0.02$. When there is no interaction between oscillators each frequency is independent from the other. Note the similarities bewteen (a) O2 and FIG 2, an isolated STNO. When $\varphi_{1,2} \neq 0$ both oscillators couple as their frequencies approach for a certain range. The coupling frequency settles in a medium frequency between both STNOs.

III B and can be added to the simulation just by adding an interacting term between oscillators in the effective field:

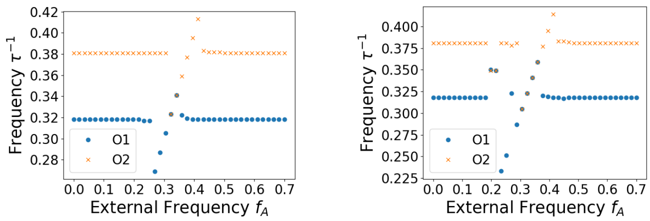
$$\vec{h}_{\text{eff}_k} = (h_0 - m_{z_k})\hat{z} + \sum_i \varepsilon_i \sin(\omega_i \tau)\hat{x} + \sum_{j\neq k}^{n} \varphi_{j,k}\vec{m}_j, \quad (7)$$

where $\varphi_{j,k}$ is the coupling constant between the j^{th} and k^{th} oscillators. The coupling constant basically depends on the distance between the STNOs. Coupling with other oscillators can be achieved with values relatively low, three orders of magnitude lower than the external magnetic field, which, again, shows how sensitive STNOs are. Note that now every STNO in the system perceives a different effective field as $\varphi_{j,k}$. Further note that the sum over the total number of STNOs, n, is restricted to $j \neq k$ as an oscillator does not have any influence over itself ($\varphi_{j,j} = 0$). In FIG 5, we change the characteristic frequency of one oscillator by rising the polarized current as we did in FIG 3 while the other oscillator frequency remains the same. When $\varphi_{1,2} = 0$ both oscillations are completely independent, however, when $\varphi_{1,2} \neq 0$ the oscillators synchronize when its frequencies are in a certain range. Note that when synchronized, their frequency settles in a medium frequency between both STNOs.

Moreover, synchronization between coupled oscillators and an external frequency can also be achieved. This is seen in FIG. 6. Note that there is no coupling between the oscillators when they are not coupled with the external frequency.

D. Coupling maps

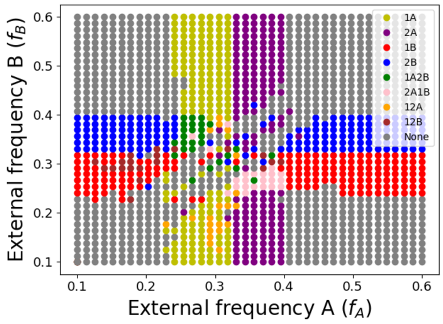
The coupling map represents the possible outputs of the system. Every possible output describes, with its singular color, a unique state of synchronization between all oscillators. For instance, if oscillator one has synchronized with the external frequency A the state would be



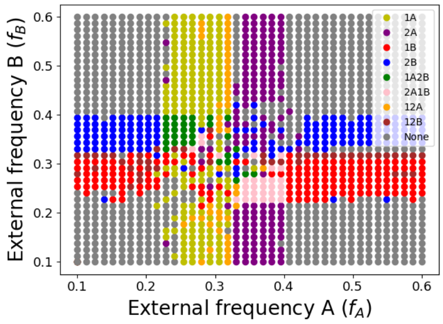
(a) $\varphi_{1,2} = 0$ (b) $\varphi_{1,2} = 0.005$

FIG. 6: Frequency of two STNOs as a function of an external frequency. $\beta_1 = 0.02$ and $\beta_2 = 0.024$. Note that when synchronized, their frequency settles in a medium frequency between both STNOs. It is just when one of them couples with f_A an lowers its characteristic frequency that is able to interact ans synchronize with the other STNO. We can also see how the synchronization range with the external frequency grows without changing ε just due to the interaction between the oscillators.

"1A". Multiple combinations may occur as there is more than one external frequency to synchronize to. This being said, the configuration of the first oscillator coupled with frequency A and the second oscillator coupled with frequency B would be "1A2B". An example of a complete coupling map of two STNOs with two external frequencies can be seen in FIG. 7. We can identify several rectangle-shaped regions that divide the map, these regions describe a state where only one oscillator couples with one external frequency, such as "1A" or "2B". We find more complex and interesting regions in the intersections of the rectangle-shaped regions. There we find states where one oscillator is coupled with a frequency and the other oscillator is coupled with the other frequency, as "1A2B" or "1B2A". These states give us very concrete information about the unknown input data due to the fact that they take a small an concrete part of the map. As seen in section III C, a realistic model of



(a) $\varphi_{1,2} = 0$



(b) $\varphi_{1,2} = 0.004$

FIG. 7: Coupling map of two nano-oscillators with (b) and without (a) interaction as a function of two external frequencies. $\beta_1 = 0.018$, $\beta_2 = 0.023$, $\varepsilon_A = \varepsilon_B = 0.05$.

a STNO system includes interaction between them. In FIG. 7 we can also see the difference between a coupling map with and without interaction. We can identify a small region in the intersection of the rectangle-shaped regions. These type of states, "12A" and "12B", give us a lot of information about one of the external frequencies, nevertheless, further oscillators would be needed to guess the unknown frequency. A big uncertainty happens in the diagonal $f_A = f_B$, as they interfere with each other and can produce several states in a small region.

Note that by changing the current applied to each oscillator (β_i) and the amplitude of the perturbations (ε_j) we can change the position and size of the different regions. This is an extremely useful tool as an STNO system is able to adapt and learn from new sets of data to give even better results.[2]

β_1	β_2	f_1 (GHz)	f_2 (GHz)	Δf_A (GHz)	Δf_B (GHz)
0.020	0.023	9.36	10.74	2.24	1.85

TABLE III: Parameters and results of the FIG.7 with a Permalloy STNO system.

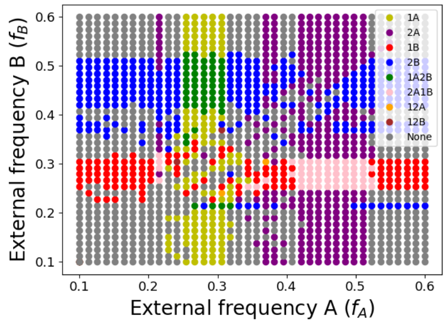


FIG. 8: Coupling map for $\beta_1 = 0.02$ and 0.033. We can see that by changing the current and the perturbations applied we can move the coupling regions for learning from new sets of data.

IV. CONCLUSIONS

We have analyzed the structure and dynamics of an STNO. We also have been able to successfully simulate multiple interacting nano-oscillators and produce different coupling maps depending on the applied current to adapt the map to new sets of data.

It is clear that STNOs are great candidates to implement ANN for their accuracy learning properties, even with their sensibility with external noise as their main drawback. However, it remains to be seen how can we overcome the challenges of practical implementation. Further research is needed in this bright and promising technology.

Acknowledgments

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[1] Macià, F., Kent, A., Hoppensteadt, F., "*Spin-wave interference patterns created by spin-torque nano-oscillators for memory and computation.*" Nanotechnology 22 (2011)

[2] Romera, M., Fukushima, A., *et al.*, "*Vowel recognition with four coupled spin-torque nano-oscillators.*", Nature vol. 563, September 2018.

[3] J.-V. Kim, "*Spin-Torque Oscillators.*" Solid State Physics 63, 217–294 (2012).

[4] T. Silva, and W. Rippard, "*Developments in nano-oscillators based upon spin-transfer point-contact devices." J. Magn. Magn. Mater. 320, 1260–1271 (2010)*