**SPU Internal Grant Final Report**

**Academic Year & Type of Grant: 2015-2016 FRG**

**PI Name: Aaron Dingler**

**Original Title of the Proposal: A Realistic Quantification of Performance in Nanomagnet Logic Systems**

1. Summarize the project goals and the activities that took place to meet those goals during the grant period. Note who was involved and if anyone was an SPU student.

My FRG proposal indicated that I would work to finish two studies of Nanomagnet Logic (NML) systems, culminating in submission of two journal papers. The proposal was for an 8-week plan starting at the beginning of July, 2015. The first study ("Study #1") involves finishing a journal paper already in progress that investigates the possibility of non-volatile, low-energy NML circuits. Study #1 required a new methodology for NML circuit simulation, in order to identify non-volatile, low-energy designs. A simulation-based study of energy requirements and stability of NML circuits was carried out using this methodology. This allowed identification of the design parameters that most greatly affect both energy and stability. The study is complete, though I ran into a couple of delays in the setup and analysis of simulation results (see #6 below). The second study (Study #2) involves finishing a journal paper that quantifies energy requirements for realistic NML clock circuitry. Part of this paper included a comparison of NML’s performance (based on the new, more realistic energy calculations) to performance projections for CMOS, the current dominant technology. As this work was started approximately three years ago, a literature search was needed to determine if the performance models for CMOS used are still relevant. My research shows that the models we used when drafting this paper are still accurate and widely used, despite the long time between the initial work and the present. A summary of findings for each study are reported in #2 and plans for dissemination in #3, below.

1. What were the major findings? If there are no findings or completed work at this time, what did you learn from carrying out this project that could be applicable to future scholarly works?

For Study #1, the major findings are 1) the new methodology to quantify energy and stability of NML systems and 2) a large design space study of NML circuits to identify which design parameters have the greatest effect on circuit stability and energy requirements. For Study #2, the major findings are 1) the methodology to quantify the energy requirements of realistic NML clock circuitry, 2) new clock circuit designs to minimize energy consumption, and 3) an updated comparison of NML energy requirements (using the new method for analysis and new clock circuit designs) to state-of-the-art CMOS equivalents. Though both studies are complete, I did not complete the papers within the original timeframe due to the extra research required to complete Study #1 (see #6 below). From this I learned valuable skills in the areas of design of experiments and how to perform detailed statistical modeling to determine which design parameters are the most important. I have set aside time during August 2016 to perform final revisions of each paper and submit to relevant journals.

1. How were or will the results be disseminated (publication, presentation, creative work, etc. – be as specific as possible)? Please add an addendum or link to completed projects or provide a time-line for future dissemination.

As mentioned in #1 above, two journal papers will be submitted (one related to each study). The paper written in Study #1 will be submitted to the *ACM* *Journal on Emerging Technologies in Computing* (JETC). The paper written in Study #2 will be submitted to the journal *Transactions on Nanotechnology* (TNANO). Both JETC and TNANO are highly regarded in the field of emerging device technologies. The revised goal is to submit both papers by the end of 8/2016.

1. What future scholarly works will be related to this project?

The ultimate goal of these two studies is to identify *realistic* designs for NML circuits, i.e., ones that can be created in an integrated circuit fabrication laboratory. The next step is start a dialogue with NML experimentalists in order to fabricate designs of interest. Fabricating these circuits will be another (large) step toward creating a functional large-scale NML system.

1. Is there external funding that you would like to pursue with the [Office of Sponsored Programs](http://blog.spu.edu/csfd/external-grantssponsored-programs/)?

Not at this time.

1. Did you run into any problems or difficulties in completing the project? How were these resolved?

For Study #1 I proposed to use the Taguchi Methods for design of experiments (i.e., simulations), which gives a structured way to carry out the simulations, and to present and analyze simulation results. One of the main benefits of the Taguchi Methods is that it reduces the required number of simulations in the design space, saving a significant amount of time (both in setting up, running, and extracting results from the simulations). The set of simulations I suggested in my proposal was, unfortunately, based on a naive design methodology. Specifically, for the experiments in this study, we know some are inherently faulty and won't yield useful results. This leaves "holes" that must be accounted for in the design of experiments in order to allow for a complete analysis. The design of experiments I initially chose did not adequately account for these holes. In my research, I found the correct way to design the set of simulations, but was unable to find clear instructions for how to perform the analysis of the results based on this design. To clear this up, I obtained a book via inter-library loan that has a more detailed explanation than the examples online and in research papers. By reading this book I learned the correct method to perform a study with a mixed number of levels -- i.e., one in which the design variables do not all have the same number of possible values. This type of design required modifying one of the standard Taguchi orthogonal arrays to fit our design space. Unfortunately, doing so resulted in a set of simulations with many extra and/or redundant simulations. Despite continued research I was not able to determine how to handle these extra simulations in the analysis of simulation results. In any case, this large number of extra simulations reduced the usefulness of the Taguchi Methods – namely, lowering the number of required simulations and thus saving time. Therefore, I abandoned this in favor of a full factorial design which offered a more straightforward way to design and analyze the set of simulations. The drawback of a full factorial design is the significantly increased number of simulations required, but these have been completed.

No major difficulties were encountered with Study #2.

1. If you had student participation – how did participation in this project further their professional goals or vocational understanding?

N/A