An All-Digital Cantilever Controller for MRFM and Scanned Probe Microscopy using a Combined DSP/FPGA Design

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ABSTRACT

An all-digital cantilever controller for magnetic resonance force microscopy (MRFM) was developed through a close collaboration between SC Solutions, Cornell University, and the U.S. Army Research Laboratory. The advantage of an all-digital controller is its absence of thermal drift, as well as its great tuning flexibility. This versatile controller is comprised of a Field Programmable Gate Array (FPGA) connected via a low-latency interface to an analog input, an analog output, and a Digital Signal Processor (DSP) with additional analog outputs. Performance of the controller was demonstrated in experiments employing ultra-sensitive silicon microcantilevers fabricated at Cornell University's Nanoscale Science and Technology Facility. The all-digital cantilever controller successfully measured 5 millihertz shifts in a 5 Hz detection bandwidth in the resonance frequency of these ultra-sensitive microcantilevers on a millisecond timescale. Independently, a noise floor of 40 microhertz in one second was measured for this controller.

Keywords: all-digital cantilever control, MRFM, FPGA, DSP

1 INTRODUCTION

The magnetic resonance force microscope is a sensitive new technique for detecting nuclear magnetic moments (and unpaired electrons) [1,2]. MRFM is providing researchers the unprecedented ability to acquire, nondestructively, a three-dimensional image of subsurface nanoscale features with isotopic, and potentially chemical, selectivity. This unique instrument will be invaluable to researchers and product developers in the semiconductor, materials, and biotechnology industries. The goal of the research reported here was to develop an all-digital cantilever controller for a prototype magnetic resonance force microscope capable of ultimately detecting the nuclear magnetic resonance signal from one proton. The paucity of tools for imaging materials with nanoscale resolution is presently a significant barrier to development of such technologies. The research summarized here represents a significant step towards development and commercialization of a magnetic resonance force microscope for studying organic material at the nanoscale.

2 CANTILEVER CONTROL

Within Scanned Probe Microscopy (SPM), active control of the cantilever is needed for several reasons:

- Fast damping of the cantilever is needed to increase imaging speed in AFM. Cantilevers with a high quality factor have lengthy ring-down time (many 10's of seconds) that slows imaging.
- AFM imaging with constant frequency and/or imaging with constant amplitude will provide different images. Both types of imaging require feedback control.
- In MRFM mode, the cantilever thermo-mechanical oscillations can be many nanometers. These random oscillations must be damped to below 0.1 nm rms if atomic-scale imaging resolution is to be achieved.
- As the cantilever approaches a surface, its natural frequency can change significantly. For many applications it is favorable or required to track and measure the cantilever frequency continuously.

To accommodate these requirements, a generic cantilever controller was proposed as shown in Figure 1.

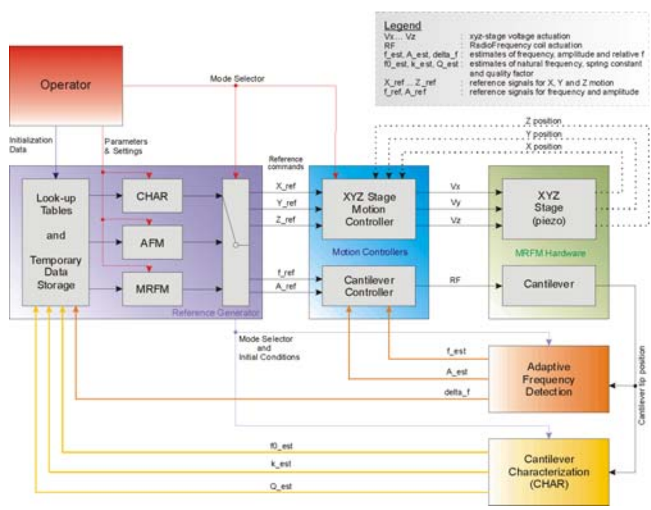

Figure 1: Schematic of generic cantilever controller.

Current analog cantilever controllers suffer from significant thermal drift and are not easily tunable [3,4,5,6]. To overcome this, an all-digital cantilever was developed that combines frequency shift measurements, phase shifting and amplitude control, as well as positive feedback control for driving the cantilever at resonance frequency [7,8,9]. This versatile controller is comprised of a Field Programmable Gate Array (FPGA) connected via a low-latency interface to an analog input, an analog output, and a Digital Signal Processor (DSP) with additional analog outputs.

3 HARDWARE DESIGN

For our feedback controller we chose a Texas Instruments (TI) digital signal processor (DSP) based system tightly coupled to a field programmable gate array (FPGA). The FPGA communicates directly through digital data lines to a high speed (80 MHz) ADC and DAC.

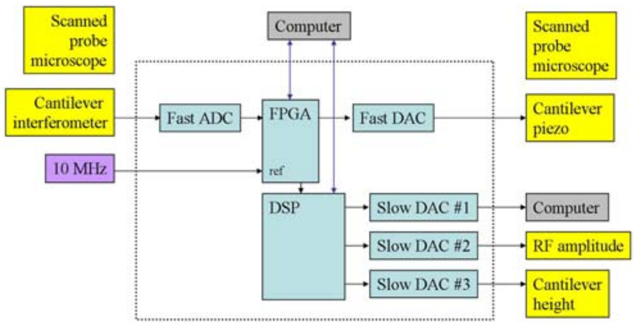

Figure 2: Block diagram of cantilever controller.

As can be seen in Figure 2, the signal path is SPM-ADC-FPGA-DAC-SPM. The Scanned Probe Microscope system provides a signal which is proportional to a cantilever position. The ADC digitizes this signal at 80 MHz and passes it to the FPGA. The FPGA computes an estimate of the cantilever's frequency, amplitude, and phase. It also sends a phase-shifted AC signal to a fast DAC which is used to drive the cantilever at its resonance frequency, thus closing the control loop. By using the FPGA to perform all the calculations in the critical path of the control loop, the overall system latency is reduced by eliminating the need to pass data to and from the DSP over its input/output bus.

The DSP controls the FPGA by setting the values of several registers in the FPGA that determine the characteristics of the control loop. The DSP also sets the values in three slow (1 MHz) DACs. The slow DAC's will be used for other aspects of the scanned probe microscope. One is used to produce a voltage proportional to the cantilever frequency, and another controls RF power levels. This leaves the third DAC free to control, for example, the height of the cantilever.

The 10 MHz clock reference for the ADC/DAC is an externally provided from a stable, low phase noise crystal. The FPGA multiplies the 10 MHz up to 80 MHz using a digitally locked loop (DLL) and this 80 MHz signal becomes the clock for the ADC/DAC. We chose to provide the 10 MHz from an external source instead of using a DSP-generated clock reference to guarantee that the reference had low phase noise. To obtain the rated accuracy of the ADC/DAC low phase noise clocks must be used. A photo of the completed all-digital cantilever controller hardware is shown in Figure 3.

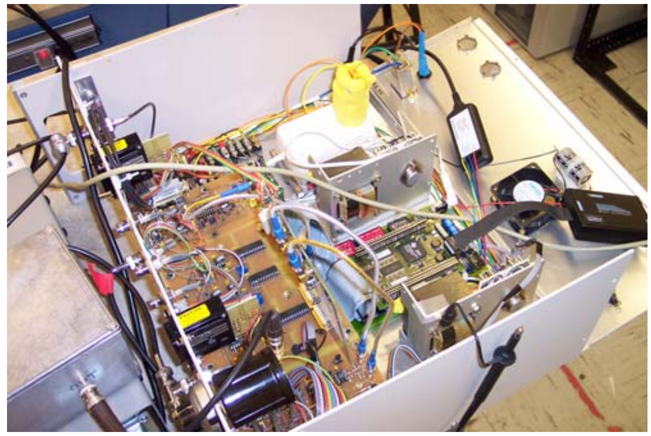

Figure 3: Controller hardware installed at Cornell.

4 SOFTWARE INTERFACE

Figure 4 shows the main User Interface. A key feature is the selection of the mode of operation. Another common feature is the display of relevant data, e.g., the current estimate of the cantilever frequency and/or frequency shift, as well as the magnitude of the cantilever signal. Another common feature is setting up the connection with the target.

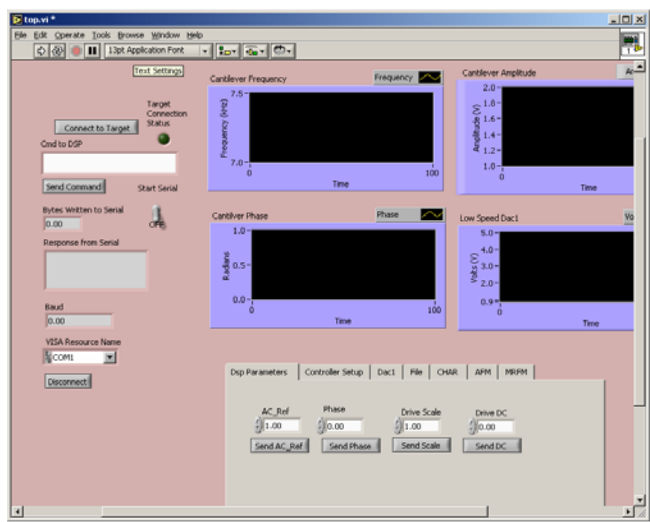

Figure 4: Screenshot of the User Interface.

5 EXPERIMENTAL SETUP

The experimental setup is shown in Figure 5. A custom-fabricated silicon cantilever with resonance frequency of roughly 7 kHz was brought within a distance *d*

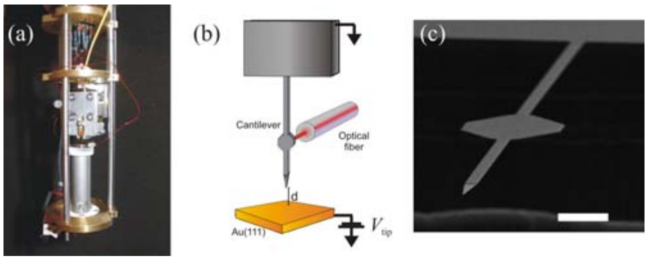

Figure 5: Apparatus for testing the cantilever controller.

of approximately 5 micrometers of a gold surface. This is far enough away from the surface that the cantilever is not affected by van der Waals forces or friction, but close enough so that the cantilever frequency can be shifted by applying a voltage V_{tip} between the cantilever and the gold substrate. In the following experiments the voltage V_{tip} was stepped up to induce a frequency shift that mimics a MRFM signal from nuclear or electron spins below the sample surface. In this way we can fully demonstrate the performance of the digital cantilever controller by detecting small frequency shifts without having to set up a full MRFM experiment. The cantilever parameters were: Spring constant: k = 7.4 × 10^{-4} N/m, Resonance frequency: f = 7373 Hz, Quality factor: Q = 2.8 × 10^{4}. The operating conditions were: Temperature: T = 300 K, Pressure: P ~ 1E-6 Torr, rms cantilever drive amplitude: z_{rms} = 55 nm, Detection bandwidth: b = 5 Hz. Under these operating conditions the minimum detectable force is calculated to be

$$F_{\min} = \left(\frac{2}{\pi} \frac{k}{f\,Q} k_{\mathrm{b}} T\, b \right)^{1/2} = 220 \times 10^{-18}\ \mathrm{N} = 200\ \mathrm{aN}.$$

The frequency noise in a 5 Hz detection bandwidth due to thermal Brownian motion of the cantilever at room temperature is calculated as

$$\Delta f_{\min} = \frac{1}{z_{\mathrm{rms}}} \left(\frac{1}{2\pi} \frac{f}{k\,Q} k_{\mathrm{b}} T\, b \right)^{1/2} = 20 \times 10^{-3}\ \mathrm{Hz} = 20\ \mathrm{mHz}.$$

For reference, the associated minimum detectable cantilever spring constant change under these same conditions is estimated to be $\Delta k_{\min} = F_{\min} / z_{\mathrm{rms}}$ = 3.9 × 10^{-9} N/m = 3.9 nN/m.

6 EXPERIMENTAL RESULTS

Using controller gain settings for a 5 Hz frequency shift detection bandwidth, a set of three experiments was performed:

a) detection of a 100 mHz shift;
b) detection of a 20 mHz shift;
c) detection of a 5 to 10 mHz shift.

For these experiments, the cantilever is driven at its resonance frequency using a positive feedback control loop [3]. In this self oscillating mode, the cantilever is used to detect a frequency shift that arises from a change in force gradient proportional to the magnetic spin moment of electrons and/or protons in the sample below the tip [2]. Driving the cantilever into self oscillation with an *analog* controller is an enormous effort, since a custom analog circuit must be rebuilt for each new cantilever with a different resonance frequency.

By contrast, the *digital* MRFM controller does not need to know the exact cantilever resonance frequency. When we connected our cantilever to the digital cantilever controller, we observed that the FPGA algorithm quickly locked on to the resonance frequency. Moreover, the controller continued to drive the cantilever at resonance frequency even when the resonance frequency was changed by an applied test voltage. In addition to driving the cantilever into self oscillation, the digital controller serves as a lock-in amplifier that detects the amplitude of the cantilever signal [7]. Figure 6 presents the results of experiments (a-c) from left to right, respectively.

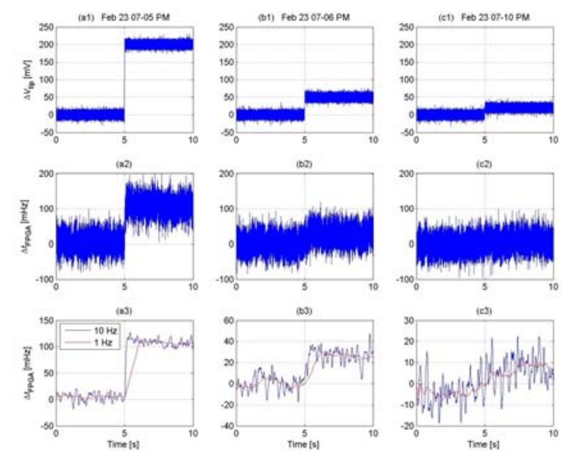

Figure 6: Frequency shift detection results.

The top figure in each column shows the step in tip voltage applied to induce a frequency shift in the cantilever. The voltage step was applied 5 seconds after the start of each experiment. The middle figure in each column shows the frequency shift estimated by the FPGA algorithm, without any filtering. Because of the fast sampling and the noise in the applied test voltage, the raw frequency estimation is fairly noisy. To better see the induced shift, this raw frequency estimate was post-processed using a moving average filter with a 10 Hz frequency gate and 1 Hz frequency gate. These results are shown in the bottom figure in each column (Figures (a3), (b3), and (c3), respectively).

From these results, we conclude that the FPGA algorithm can easily detect even the smallest frequency shift of approximately 5 mHz that was applied. This observation is in good agreement with our estimate of the minimum detectable frequency shift for this application, which extrapolates to approximately 20 mHz in a 5 Hz detection bandwidth. This agreement suggests that the frequency noise is limited by the Brownian motion of the cantilever and not by any noise in the controller.

Another estimate of the smallest resolvable frequency shift measurable with the FPGA can be obtained from a frequency-fluctuation power spectrum. In Figure 7(a) we show the cantilever frequency power spectrum (20 averages) recorded when an oscillating voltage is applied to the cantilever. Peaks in the power spectrum are clearly visible for applied voltages oscillating at 3 Hz (red curve) and 10 Hz (blue curve). A peak at 100 Hz (green curve) is present but only apparent if one expands the y-axis. The response at frequencies at the higher frequencies is attenuated, as expected given that the FPGA algorithm bandwidth is set to approximately 5 Hz. Also apparent in the power spectrum is a noise floor that rolls off at higher frequency.

The square root of the integral of the power spectrum noise floor is plotted versus frequency *f* in Figure 7(b). This square root, which has units of Hz, is equal to the root-mean-square frequency noise expected for time-domain data low pass filtered at frequency *f*. For data low-pass filtered at 5 Hz, we would predict a time-domain rms noise of ~22 mHz. This is in excellent agreement with both the 20 mHz rms frequency noise measured in a 5 Hz bandwidth using a commercial frequency counter and the 20 mHz rms variation calculated assuming that thermal Brownian motion of the cantilever is the dominant source of frequency noise in the FPGA algorithm.

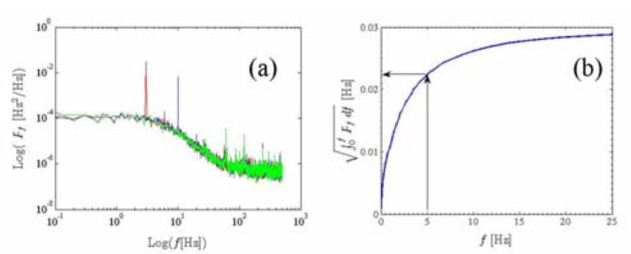

Figure 7: Frequency shift power spectrum.

7 CONCLUSIONS

An all-digital cantilever controller was developed that is well poised for commercialization as an extremely powerful and versatile scanned probe microscope controller. The controller is capable of

- driving a cantilever into self-oscillation, automatically seeking a cantilever's resonance frequency;
- estimating small frequency shifts in a cantilever's resonance frequency, as well as its amplitude of oscillation;
- providing optimal phase shifting for compensation of any hardware-induced latency.

A prototype controller was built in hardware and software and tested on one of Cornell's ultra-sensitive cantilevers. The controller quickly locked into the cantilever's resonance frequency and was well able to detect even the smallest frequency shift of approximately 5 mHz.

ACKNOLEDGEMENT

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REFERENCES

[1] J. A. Marohn, R. Fainchtein, and D. D. Smith, "An optimal magnetic tip configuration for magnetic-resonance force microscopy of microscale buried features", *Applied Physics Letters*, Vol. 73, No. 25, p.3778-3780, Dec. 1998.

[2] S. Garner, S. Kuehn, J. Dawlaty, N. E. Jenkins, and J. A. Marohn, "Force-gradient detected nuclear magnetic resonance", *Applied Physics Letters*, Vol. 84, No. 25, p.5091-5093, June 2004.

[3] T. R. Albrecht, P. Grütter, D. Horne and D. Rugar, "Frequency modulation detection using high-Q cantilevers for enhanced force microscope sensitivity", In *Journal of Applied Physics* 69(2), p.668-673, 15 Jan. 1991.

[4] U. Dürig, H. R. Steinauer and N. Blanc, "Dynamic force microscopy by means of the phase-controlled oscillator method", In *Journal of Applied Physics* 82(8), p.3641-3651, 15 Oct. 1997.

[5] Ch. Loppacher, M. Bammerlin, F. Battiston, M. Guggisberg, D. Müller, H. R. Hidber, R. Lüthi, E. Meyer, H. J. Güntherodt, "Fast digital electronics for application in dynamic force microscopy using high-Q cantilevers", *Applied Physics A* 66, S215-S218, 1998.

[6] J. Jacky, M. Ettus, J. Garbini, T. Kriewall and J. Sidles, "Using a Field Programmable Gate Array for MRFM Cantilever Control", Kavli Institute at Cornell Summer School in MRFM, June 21-24, 2006.

[7] B. Wu and M. Bodson, "A Magnitude/Phase Locked Loop Approach to Parameter Estimation of Periodic Signals", In *Proceedings of the American Control Conference*, Arlington, VA, June 25-27, 2001.

[8] G. F. Franklin, J. D. Powell, and A. Emami-Naeini, *Feedback Control of Dynamic Systems*, Fifth Edition, Prentice Hall, 2006.

[9] G. F. Franklin, J. D. Powell, and M. L. Workman, *Digital Control of Dynamic Systems*, Third Edition, Addison-Wesley, 1998.