Magnetic Resonance Force Microscopy

By Steve Thanos

When researchers at the University of Washington wanted to implement a DSP-based control system for their experiments in Magnetic Resonance Force Microscopy, they decided that a VMEbus system would be their best choice. The deciding factors were performance, flexibility, and upgrade cost.

MRFM 3D imaging

Since the early 90's, the University of Washington and IBM have been involved in developing a practical technology for imaging the 3-dimensional structure of individual molecules. This technology is called Magnetic Resonance Force Microscopy (MRFM). Like medical Magnetic Resonance Imaging (MRI), MRFM is inherently 3-dimensional and non-destructive because of the low energy excitation. This has the potential for studying molecular structures in their native environments, and materials just below the surface.

Experiments at the UW have achieved reconstructed images with 80 nm voxels. IBM scientists have achieved a breakthrough by directly detecting the spin of a single electron within a solid sample. Further development could allow this imaging technology to address needs in nanoscale engineering, materials science, molecular biology, and medicine.

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MRFM applications

Imaging technology such as MRFM has the potential to address frontiers in biology, medicine, physics, and quantum system engineering. For example, it might be used to investigate the nature of viruses such as HIV and SARS; the imaging scale might show how a group of enzymes binds to the human amyloid protein whose accumulation is implicated in Alzheimer's disease; and to study the DNA-binding protein P53 whose mutation is strongly associated with tumor malignancy. More information about these structures will lead to the development of new drugs to treat these diseases.

In physics, the discovery of the exact location of specific atoms within minute electronic structures will significantly improve integrated circuit design and industrial catalysts. This will lead to improved quality and yield in the manufacture of semiconductors and ICs.

Think of MRFM as a new electron microscope, with 100x the magnification, and less invasiveness. The impact of MRFM on these sciences may equal the impact of the introduction of the telescope on astronomy.

As Daniel Rugar, Manager of Nanoscale Studies at the IBM Almaden Research Center, relate "Throughout history, the ability to see matter more clearly has always enabled important new discoveries and insights. This new capability should ultimately lead to fundamental advancements in nanotechnology and biology."

MRFM operating principles

The operating principles of MRFM are shown in Figure 1. As shown in the figure, a sample molecule of interest is placed on the sample positioner which lies below a sharp magnetic tip. A cantilever is attached to the magnetic tip.

As the cantilever approaches the sample, it bends in response to the magnetic forces due to the magnetic nuclei in the sample

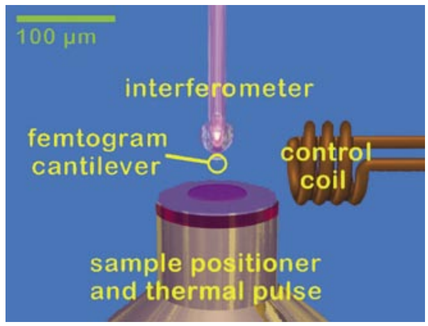

Figure 1

(many common elements, such as hydrogen, fluorine, and carbon-13 have magnetic nuclei). Nuclear magnetic resonance is used to manipulate individual nuclei within the sample that are just the right distance from the tip (i.e., nuclei within the *resonant slice*).

The control coil in the figure is used to apply a suitably modulated Radio Frequency (RF) magnetic field, which causes the magnetic moment of the nuclei within the resonant slice to be flipped up and down sequentially.

The resulting alternating force on the tip causes the cantilever to vibrate slightly. This vibration is detected using a sensitive fiberoptic interferometer.

The sample is then scanned with respect to the tip, and an image of the sample's atomic structure appears on a computer display.

Only spins within a thin resonant slice are affected. The spins closer to the tip are in a field that is too strong for resonance, while the spins farther away from the tip are in a field that is too weak for resonance. Therefore, only the spins within the resonant slice exert a magnetic force that is detectable by the cantilever. The stronger the gradient of the magnetic field, the thinner the resonant slice. Current slice thickness is less than 10 nm.

Block diagram

The block diagram for the MRFM system is shown in Figure 2. The MRFM assembly is housed in a cylindrical structure that achieves a vacuum of 10^{-5} Torr or higher at 100 K (-173°C).

The force-detecting element is a commercial cantilever with a resonant frequency less than 7 kHz, with an attached 5.8 µm diameter magnetic strip.

A high-voltage amplifier whose input is generated by a waveform synthesizer drives the sample positioner. A 3-turn coil, 120 µm in diameter, produces resonant microwave or RF fields. The coil is driven via a vacuum feedthrough from RF (DC to 40 MHz) or microwave (1 to 20 GHz) synthesizers, which are amplitude- or frequency-modulated. A larger coil provides audio frequency feedback to the cantilever from the DSP controller.

A fiber interferometer detects the cantilever motion. The effective interferometer noise floor expressed in terms of cantilever displacement is 0.016 Angstrom/Root Hz, or an equivalent thermal noise temperature of 0.30 mK.

A battery-isolated photoreceiver converts the interferometer output to a voltage signal that's applied to a lock-in amplifier and the DSP controller for stabilizing the cantilever.

Adaptive control and diagnostics

A critical element of MRFM imaging is the active control of cantilever dynamics. Control accomplishes three goals to enhance the effectiveness of soft, high-Q (the mechanical factor) cantilevers:

- It broadens the cantilever's response bandwidth.
- It reduces the system damping time.
- It lowers the thermal noise vibration amplitude, thereby improving the Signal-to-Noise Ratio (SNR).

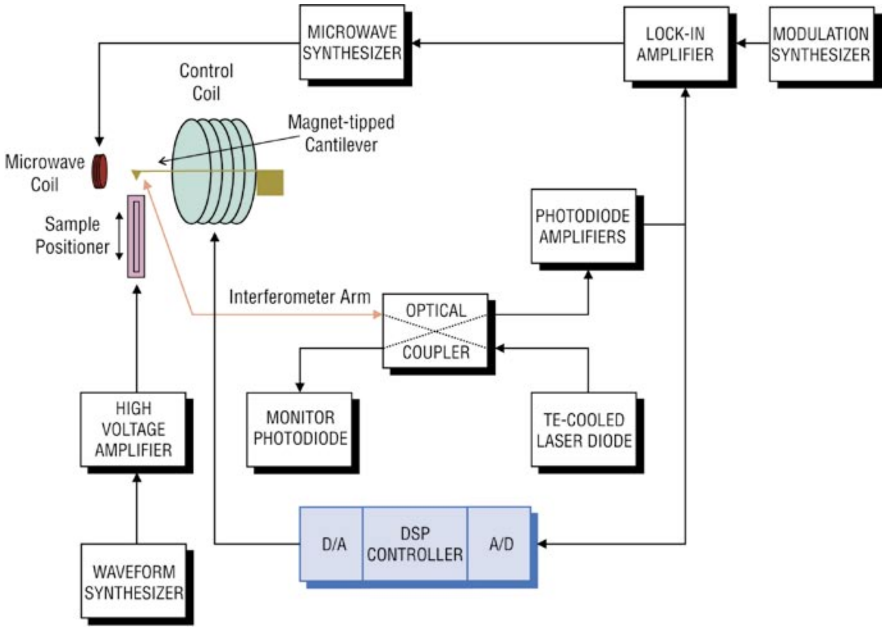

Figure 2

A block diagram of the control and diagnostics system is shown in Figure 3. The control force is generated through a magnetic field from the large coil which acts on the magnetic tip. An optimal controller strategy that balances the control effort and the position accuracy satisfies the requirements of most magnetic resonance systems.

Optimizing the MRFM process

MRFM has two main limitations. First, it is most effective at cryogenic temperatures where thermal molecular motion is greatly reduced, and thermally induced noise is at a minimum. Second, forced microscopy requires nuclei with non-zero electron spin.

To improve MRFM measurement sensitivity, the following parameters have been optimized:

- The operating temperature has been reduced.
- The magnetic gradient has been maximized.
- The cantilever size has been reduced.
- The cantilever resonance has been increased.
- The cantilever damping time has been increased.

These optimization principles work extraordinarily well in practice. Since the start of this research in 1992, the MRFM Signal-to-Noise Ratio (SNR) has improved by an incredible 112 dB.

The VME solution

The DSP controller and diagnostics for a one-dimensional MRFM system is shown in Figure 4.

The Pentek Model 4294 VME processor board features quad Motorola MPC7410 PowerPC processors, and runs under the VxWorks RTOS. Each processor is equipped with its own VIM (Velocity

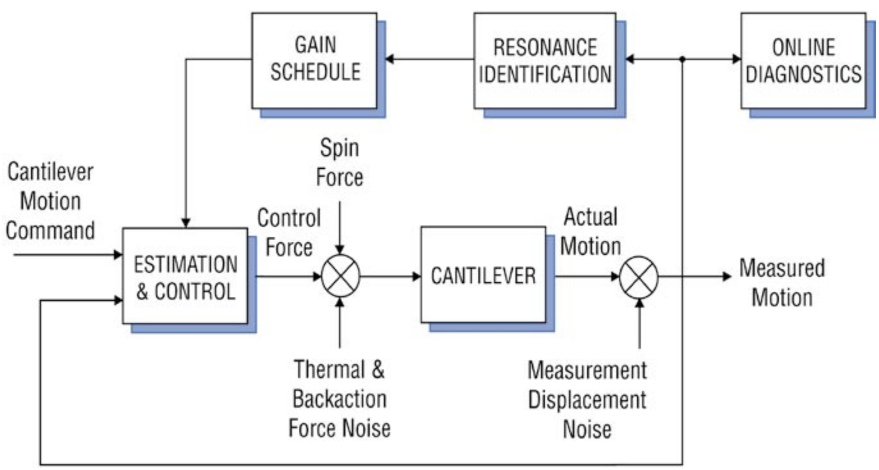

Figure 3

Interface Mezzanine) connector, providing a local high-speed synchronous bidirectional FIFO (BI-FIFO) which buffers 32-bit parallel data transfers between the mezzanine module and the MPC7410.

The Pentek Model 6216 Dual Wideband Receiver and A/D VIM-2 Module features two complete channels of signal processing. Each channel has a 12-bit A/D converter with sampling up to 65 MHz, and a digital downconverter with an output bandwidth up to 25 MHz.

The Pentek Model 6229 Dual Digital Upconverter and D/A VIM-2 Module features two complete channels of interpolation and frequency translation. Each channel has a 12-bit D/A converter with an analog output from DC to 80 MHz, and a digital upconverter. The 6229 provides the analog output control voltage, and uses the 6216 sync bus signal for synchronization.

The 4294 communicates with the Sun Blade Workstation via the 10/100 BaseT Ethernet front panel port. This is useful for downloading development code, debugging, and streaming data out of the system for tasks such as simulation comparison.

The implemented VME solution offers a side benefit, the processor board with the attached VIM-2 modules uses a single slot in the VME enclosure, which leaves several slots open for future expansion. Ω

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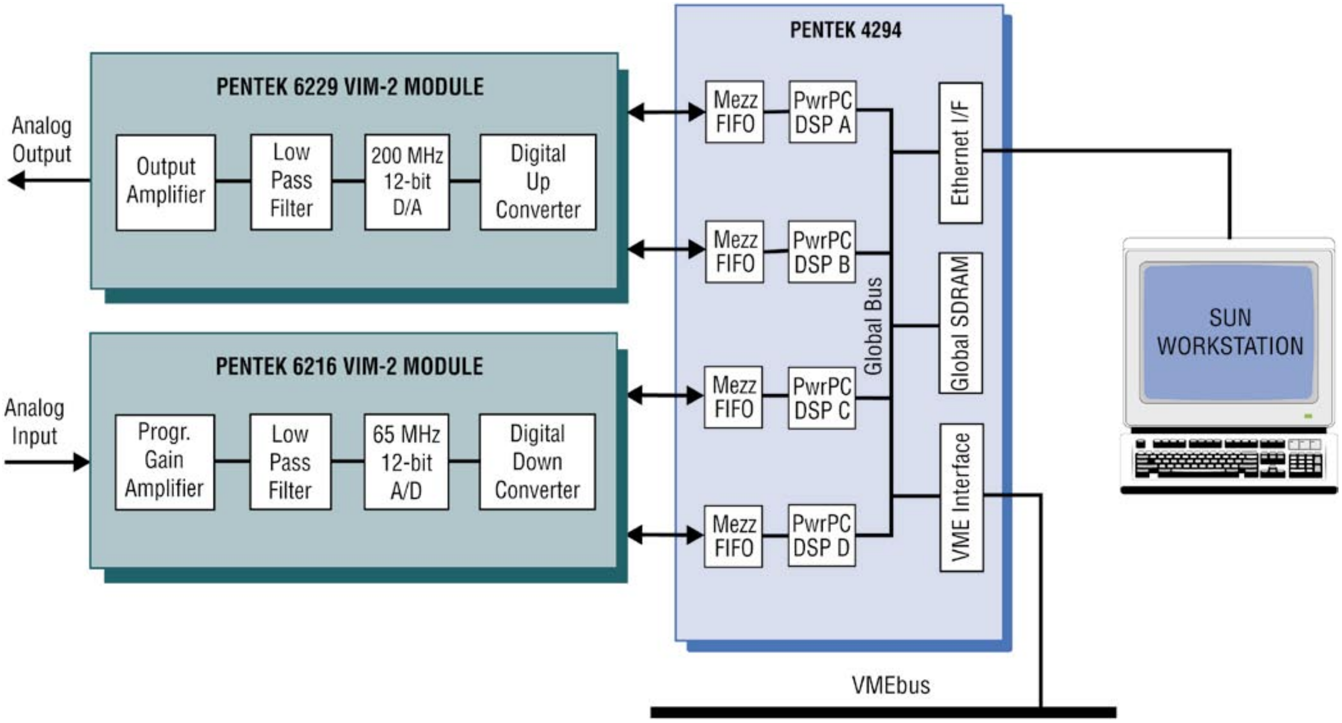

Figure 4