AFM: fast, furious and on-a-chip

From video-rate to on-chip atomic force microscopy, meet the man – Professor Reza Moheimani – who is revolutionising AFM, reports Rebecca Pool

Earlier this year, Professor Reza Moheimani and colleagues from the Laboratory for Dynamics and Control of Nanosystems, University of Texas at Dallas, unveiled a 1 cm^2 MEMS-based atomic force microscope that they believe will revolutionise this field of microscopy.

Attached to a small printed circuit board - containing circuitry, sensors and miniaturised components to control device movement - the AFM-on-a-chip prototype operates in tapping mode and right now, attains better than 1 nm lateral resolution. Crucially, the device is likely to carry a price tag of only a few thousand dollars, at least an order of magnitude less than conventional AFMs.

As Moheimani tells Microscopy and Analysis: "Right now, atomic force microscopy is out of reach for many, many laboratories not just in developing nations, but in countries world-wide."

"But if the price can come down like this, then every laboratory in the world could have access to an AFM," he adds.

For Moheimani, the road to on-chip AFM started nearly twenty years ago, when he first came across conventional instruments, which were, as he says, 'really slow'.

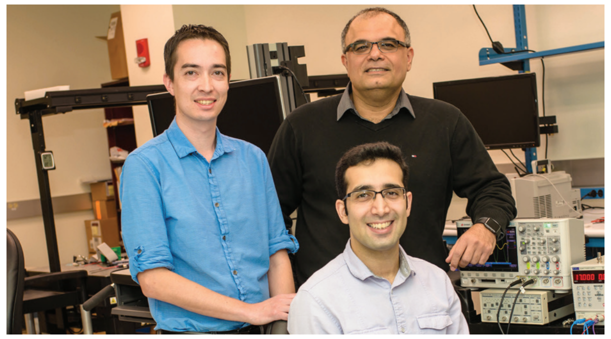
"I was amazed at what a slow system it was and saw no reason why it could not be made to operate faster," says the researcher. "Since this time I have been looking at ways to make video-rate imaging happen."

Following his PhD in Electrical Engineering from the University of New South Wales, Australia, Moheimani moved over to the University of Newcastle, Australia. Here he founded and directed the Laboratory of Dynamics and Control of Nanosystems, which would eventually become a multi-million dollar state-of-the-art research facility for driving systems theory and control engineering forward, for nanotechnology applications.

Focusing on mechatronics, the researcher spent a lot of time developing nanoscale positioning systems for high speed scanning probe microscopy, and come 2015, re-located his laboratory to the University of Texas at Dallas, where research has continued with gusto. Today the laboratory boasts myriad control systems breakthroughs, all of which have contributed to video-rate AFM on dynamic samples with images, several microns in size.

"If you want to build a high-speed AFM you have to make all of its components very fast," highlights Moheimani. "You need to have a nanopositioner or scanner that moves your samples over your imaging window really fast and you need to have a cantilever that can interact with the sample at high bandwidth."

"You also need to have good lateral and Z-axis control systems, so we have been developing the technology for all these AFM components," he adds.



TEAM Professor Reza Moheimani (top right) and researchers from the Laboratory for Dynamics and Control of Nanosystems, University of Texas at Dallas

ROBUST CONTROL

For example, the researchers have designed and fabricated high-stroke, high speed nanopositioners and implemented high bandwidth feedback controllers for the AFM Z-axis feedback loop. They have also developed a framework for robust control of the quality factor in AFM microcantilevers and established methods to quickly estimate AFM microcantilever amplitude and phase.

"One idea that I had for a long time is why limit yourself to a rastering-type movement as your scanner has to cope with very high frequency motion as the cantilever turns corners," he highlights. "So we've developed several smooth, non-raster scanning patterns including one based on a spiral and also a Lissajous curve."

"These alternative patterns allow us to scan samples really, really quickly compared to what we could do with conventional rastering," he adds.

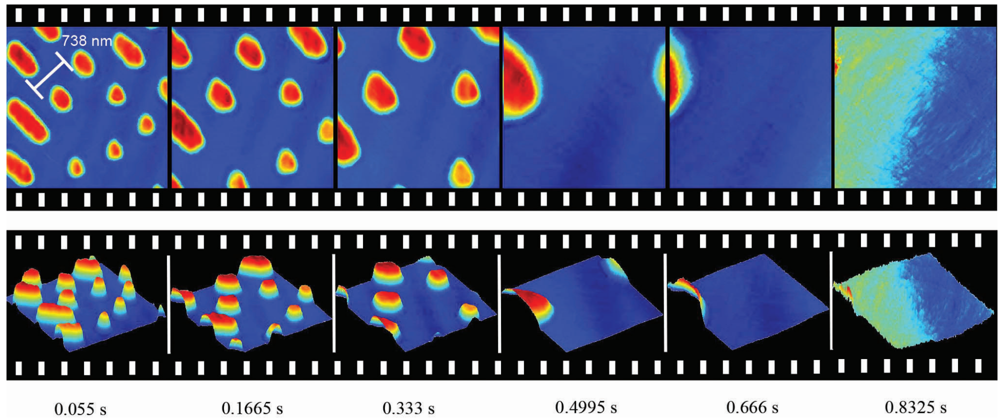
In the last two years Moheimani and his team have combined their technology breakthroughs with the cantilever and optical sensor of a conventional AFM to achieve a scanning speed of 37.5 frames a second with a circular-shaped image diameter as large as 3000 nm. Resolution is compatible with conventional AFM.

Right now, the researchers have imaged moving calibration gratings and are now working with numerous colleagues, including researchers in the bioengineering department at UT Dallas, that want to image the dynamic properties of DNA and other bio-molecules in native environments.

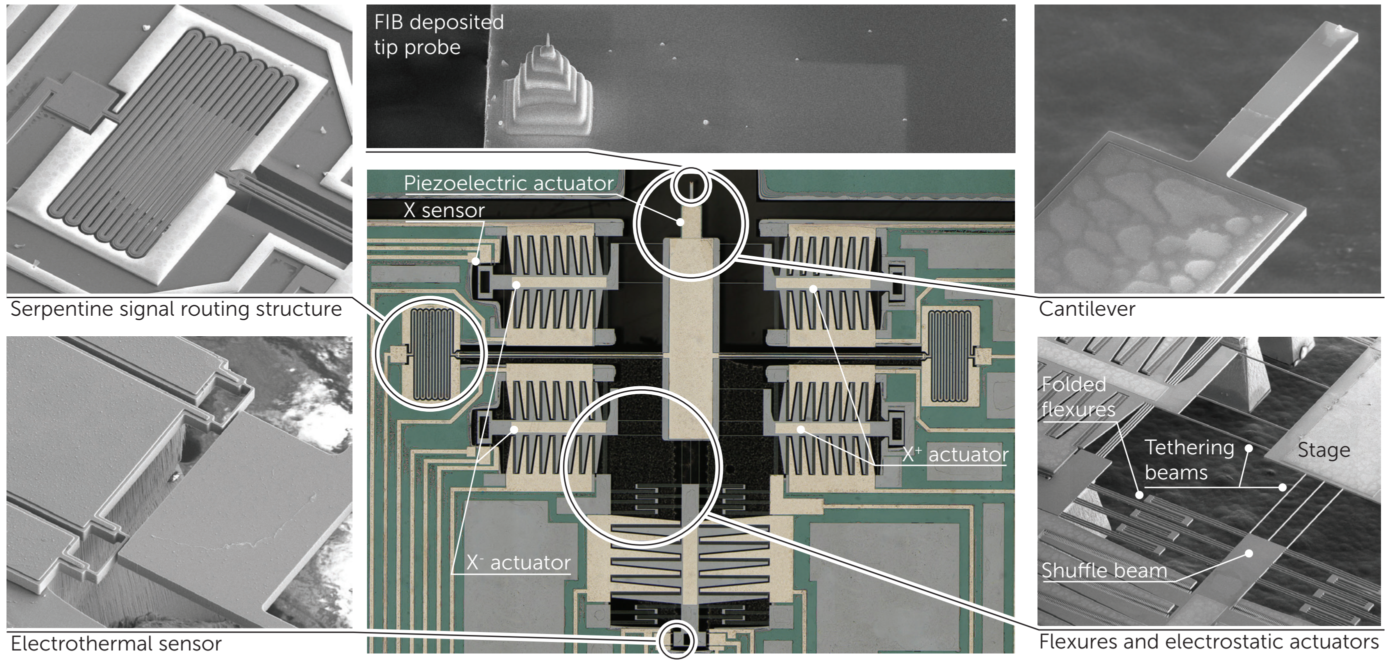
"All of our work has taken place using contact mode at a constant force, but this collaboration provides one of our motivations for developing video-rate tapping mode AFM," says Moheimani. "We have been fabricating smaller cantilevers that have much higher resonance frequencies and are now well on our way to demonstrating tapping mode video rate AFM with similar scanning sizes [to contact mode]."

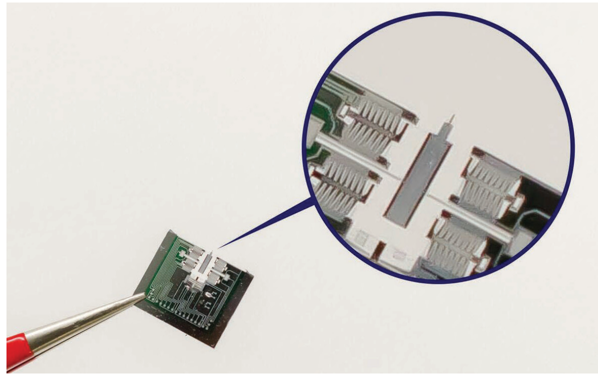
Moheimani reckons, video-rate tapping mode AFM will be in hand within the next two years. But as well as speed, the researcher has also had size on his mind, and alongside colleagues, has been busy miniaturising AFM itself.

Moheimani's inspiration for on-chip AFM, came from a short stint at IBM Zurich Research Labs during the Summers of 2007 and 2008 - where he collaborated with researchers on IBM's ambitious Millipede project. Put simply, the IBM Millipede is a non-volatile computer memory based on an array of thousands of v-shaped, 70 micron-long cantilever tips that indent the storage medium - a polymer film - to record digital data. Crucially, the polymer film can be positioned with nanometre-scale accuracy, relative to the cantilever array, using microelectromechanical systems (MEMS).



AFM A series of Lissajous-scanned AFM images obtained at 18 frames/sec. Images show the process of fast zooming in on a sample area from 3 µm × 3 µm to 200 nm × 200 nm, only showing every third image in the series





FABRICATED on-chip AFM, with close-up SEM images highlighting the major components of the device (top)

ATOMIC force microscopy on-a-chip (above)

Thanks to rival Flash memory, commercial success never ensued for Millipede at the time, but having helped to design its sophisticated control systems, Moheimani left IBM and returned to his research group, then at the University of Newcastle, with a burning ambition to build a miniaturized AFM.

"Of course at the time I was working on more conventional AFM control problems, but I still had to overcome many challenges to make miniaturised AFM happen, with the main one being that I knew nothing about MEMS," he says.

Undeterred, Moheimani proceeded and having got to grips with microelectromechanical systems, set to work on what is now called 'on-chip AFM'.

On the macroscale, the conventional AFM typically uses piezoelectric tube scanners to guide the microcantilever in-plane during scanning. At the same time, the deflection of the cantilever is measured using a laser and optical sensor.

However, Moheimani and colleagues have now delivered their miniaturised, stripped down version of AFM, based on MEMS technology, that operates in tapping-mode and fits entirely onto a 1 cm^2 computer chip.

As he highlights: "If you can put all the functionalities of an AFM on a silicon-on-insulator chip, then the cost of fabricating large numbers becomes quite small. And you can then build pocket-sized MEMS devices that you can take to the field for experiments."

MEMS MOTION

As part of the on-chip AFM design, Moheimani and colleagues decided to replace the piezoelectric actuators used in lateral scanning by a conventional AFM, with MEMS versions. In the current set-up, MEMS electrostatic actuators position the device's central stage while electrothermal sensors enable closed-loop position control of the stage.

"Piezoelectrics are probably the best actuators that we have for nanopositioning, everyone uses them, but these devices do cause many problems," he says. "They're actually non-linear actuators with hysteresis that gives way to piezoelectric creep."

"So moving to MEMS was a natural move for building the scanners for the AFM," he adds.

The researchers are also developing a new cantilever deflection system by replacing the laser and optical sensor with a single piezoelectric transducer. As part of the on-chip set-up, a silicon microcantilever is integrated at the end of the device's central stage, and is actuated, out-of-plane, using this transducer.

As Moheimani highlights, this transducer will also measure the deflection of the cantilever, removing the need for a laser and optical detector.

Importantly, the researchers have used the device to obtain tapping-mode AFM images, with an imaging range of up to 8 µm by 8 µm in closed loop.

But plans don't stop here. Moheimani and colleagues now wish to draw on their decades of AFM development and deliver video-rate on-chip AFM by combining the on-chip scanner with the non-raster scan methods already developed in their macro-scale video-rate AFM.

"We're working very hard to develop new displacement measurement methods that can be incorporated into the tiny cantilever on a single MEMS chip," says the researcher. "The big challenge is to get this technology to work when you've shrunk the size of the cantilever, but I would say we are only a couple of years away from doing this."

To date, Moheimani's AFMs have functioned under ambient conditions, but he is also working with a US-based company to develop on-chip AFM that can be used in a vacuum and in non-contact mode. He is also hoping to start developing an on-chip scanning tunnelling microscope with the company.

Critical to this, Moheimani is adamant these devices satisfy the requirements of genuine researchers. "If [the performance] gets close or maybe even better than, say, a commercial atomic force microscope that you buy for \$100,000, \$150,000, then I think this is going to have a massive impact," he says.