Reza Moheimani (left) and his wife, Niloofar, enjoying a drink with Ian Petersen and his wife, Lynn, at the 2016 American Control Conference.

S.O. REZA MOHEIMANI

Q. Congratulations on receiving the 2018 IEEE Transactions on Control Systems Technology Outstanding Paper Award. What can you tell us about the work that led to this recognition?

Reza: Thank you. I am honored and humbled to have received this award for the second time: a paper that I coauthored 12 years ago received the Best Paper Award from *IEEE Transactions on Control Systems Technology* in 2007. I have been publishing in *IEEE Transactions on Control Systems Technology* for two decades. I am, and have always been, impressed with its strict and thorough review process and high standards. It is a true honor that our work was selected out of a large number of excellent papers published in this journal in 2016 and 2017 to receive this recognition.

The research reported in this paper (coauthored with my former Ph.D. student, Dr. Michael Ruppert) is a contribution to atomic force microscopy (AFM). The atomic force microscope is a sophisticated mechatronic system that uses a microcantilever force sensor to study topographical features and inherent material properties at the nanometer-length scale. In conventional dynamic mode AFM, the microcantilever is excited at its fundamental resonance frequency, and nonlinear force interactions between an atomically sharp tip and the surface are used to determine material properties. However, a microcantilever has many modes, and researchers have found that operating it simultaneously in several modes unravels important material properties beyond what could be gleaned from conventional AFM. This method is known as multifrequency AFM (MF-AFM).

The key to achieving the true potential of this method is the ability to control dynamics of these higher frequency modes. In this paper, we proposed a robust feedback controller that enables arbitrary control of microcantilever quality factors. This enabled us to experimentally demonstrate improved imaging stability and higher cantilever bandwidth while imaging nanoscale features. In addition, we were able to achieve higher scan speeds by reducing the transient response of microcantilever resonant modes.

This work is particularly important in enabling video-rate MF-AFM, a technology that does not yet exist. There has been a lot of interest for a long time to speed up the atomic force microscope to enable the capturing of dynamic properties of active materials and biologically relevant specimens at nanoscale and in real time. These efforts have led to interesting progress. However, all the work has been concentrated on the conventional AFM and I realize video-rate MF-AFM will require further developments along the lines of the work reported in this paper.

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Q. You recently moved from the University of Newcastle, Australia, to the University of Texas (UT) at Dallas. What can you tell us about this move?

Reza: I was with the University of Newcastle for 18 years. I had an outstanding research team and a fantastic laboratory that I worked hard to build over those years. I was part of an excellent controls group with good collaborators. In addition, Newcastle is a beautiful place to live. Leaving all that behind to move, not just to another institution but to another continent, took some courage and some thinking, nearly two years, I should say. Now, of course, I am with a good university, I am part of a very good controls group that's growing, I have already established my laboratory, and, being a researcher, I know that opportunities to do exciting research in the United States are unparalleled.

I'm also pleased that I left something behind—the laboratory that I established in Newcastle is still there, and my former students and postdocs are there producing important results. On a personal level, the first six months were quite hectic. Finding a new home, new schools for our children, a couple of new cars, and, believe it or not, getting a Texas driver's license were among many things that kept us preoccupied. After that, however, things slowly got back to normal, and I was able to pay more attention to my research, which is the main reason I'm here now.

Q. How did this move affect your research and your access to research funding?

Reza: Moving to UT Dallas had important implications on my research.

(From left) Steve Yurkovich, Graham Goodwin, Reza Moheimani, and Mark Spong, enjoying dinner at a Dallas steakhouse.

Reza Moheimani and his wife, Niloofar, with their children aboard the USS *Midway* in San Diego, California.

I have been interested in control of high-precision mechatronic systems for a long time, the atomic force microscope being one example of such systems. Many of these systems are macroscale to mesoscale devices that are required to reach nanoscale-positioning accuracies. I had this idea for a long time that it should be possible to improve the performance of these systems through miniaturization. The best technology for this purpose is microelectromechanical systems (MEMS). Before moving to UT Dallas, I was using a multiuser MEMS process to build MEMS devices. This was convenient but rather limiting in terms of fabrication capabilities. Now, at UT Dallas, I have access to a well-equipped clean room that I extensively use for MEMS fabrication. My laboratory is now set up so that we can design MEMS transducers and build them in the clean room. We are well equipped for MEMS characterization and packaging. In addition, we have extensive experience with the modeling and control of these devices. There may be only a small number of labs that have a similar breadth.

With regards to research funding, one must be ready to face many challenges when moving to a new academic environment. The biggest challenge is perhaps getting used to a completely new funding system. Most nonmedical research in Australia is funded by the Australian Research Council (ARC). ARC funding is quite competitive, but you get to apply once a year, and guidelines are fairly stable. The research funding scene in the United States, however, is much more dynamic. There are numerous funding agencies, many of them mission oriented, with program managers exploring new areas all the time and goalposts shifting yearly. Transitioning from the system I was familiar with to this new funding environment required some effort. However, I have been able to raise the funds I needed to do my research thus far.

The first research project I had after moving to UT Dallas was funded by DARPA under the Atoms to Product Program. The goal of this program was to conceive technologies for assembly of nanometer-scale to micrometer-scale components. My project involved dealing with the problem of tip crash in the scanning tunneling microscope (STM). The STM is used to image material surfaces with atomic resolution. It is also used for atomically precise lithography on hydrogen-terminated silicon, which is the initial step for atom-by-atom manufacturing.

The STM works based on the quantum mechanical phenomenon of tunneling. When a metallic probe possessing a sharp tip is brought within a 1-nm distance of the surface of a conducting or semiconducting specimen (and when a voltage difference is established between the two objects), it results in a tunneling current from an atom on the apex of the tip to an atom on the surface. In STM, this current is measured and regulated by a proportional-integral controller (that is, the controller adjusts the probe's height so that the tunneling current remains constant). The control signal is then used as the topography estimate. Lithography works based on the same principle, but with a bias voltage of opposite polarity.

Tip crash is prevalent in scanning tunneling microscopy. It is very

The atomic force microscope is a sophisticated mechatronic system that uses a microcantilever force sensor to study topographical features and inherent material properties at the nanometer-length scale.

common for the STM tip to come into contact with the surface during imaging. While this has been taken for granted and tolerated by STM users for decades, it is a major concern in STM-based lithography and a key obstacle in making this technology commercially viable. With DARPA's support, we were able to identify the cause of this long-standing problem. It turns out that there is a parameter in the dynamics of the system that changes as the tip moves from one type of atom to another or when a tip change occurs, with the latter being a common feature in the STM. This quantum mechanical parameter is known as the local barrier height (LBH) and is the average work function of the tip and surface. We were able to show that the LBH appears as a gain in the dynamics of the STM, and using a model that we obtained through closed-loop system identification, we were able to establish that it could destabilize the STM closed-loop system. We then proposed a method to identify the LBH on the fly and update controller gain adaptively to counter LBH variations. This method is now patented and programmed into an STM control system marketed by Zyvex Labs, LLC. It is a good feeling when one's research results in a commercial product, particularly one that helps others develop new products and devices with potential game-changing outcomes.

I also lead a recently awarded emerging exploration research project funded by the U.S. Department of Energy's Advanced Manufacturing Office under the Atomically Precise Manufacturing Program. This project is aimed at developing the infrastructure to enable high-throughput atomically precise manufacturing hundreds of times faster than what is possible with the conventional approach that uses a single-tip scanning probe microscope to perform atomically precise lithography. The key objective is to develop tools and processes to create ultraminiaturized systems and devices with atomic precision and unprecedented capabilities. An immediate application is in the field of silicon quantum electronics, where other researchers have demonstrated a variety of new devices such as single-atom transistors, quantum-computing qubits, and few-atom quantum dots with hydrogen depassivation lithography using single-tip STM.

Moving these innovative quantum electronic devices out of physicists' labs and turning them into products will require atomically precise lithography at rates that may seem unimaginable today. Our approach is to design MEMS STMs that can be scaled up to function in large arrays to enable high-throughput atomically precise lithography. We can design these new devices so that they are significantly faster than conventional STMs. Furthermore, operating them in an array will significantly increase their throughput. The control of such systems requires positioning a large array of STM tips independently over an atomic lattice with subatomic precision and ensuring that each tip's feedback loop is fast and robust. We aim to demonstrate the feasibility of this approach during the course of this project. In addition, we have been awarded an STTR project that enables us to transfer technologies we develop to U.S. industry.

Q. What control courses are you teaching at UT Dallas?

Reza: I have been mainly teaching graduate courses at UT Dallas. I teach linear systems, which is a core course for graduate students who wish to specialize in systems and control in the systems engineering, mechanical engineering, or electrical engineering departments. I have developed a graduate course on optimal estimation and Kalman filters. Similar courses are

(From right) Reza Moheimani, Masayoshi Tomizuka, and Roberto Horowitz at the 2018 American Control Conference awards reception.

Profile of S.O. Reza Moheimani

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- *IEEE Control Systems Society experience highlights:* Board of Governors (2016); associate editor, *IEEE Transactions on Control Systems Technology* (2004–2011); guest editor, *IEEE Transactions of Control Systems Technology* (2001, 2007, and 2012); program chair, IEEE Multi-Conference on Systems and Control (2015); chair, IEEE Transactions of Control Systems Technology Outstanding Paper Award Committee (2015–2017), Control Systems Technology Award Committee (2018–2020).
- *Notable awards:* IEEE Transactions on Control Systems Technology Outstanding Paper Award (2007 and 2018); Control Systems Technology Award (2009); Fellow, IEEE, International Federation of Automatic Control (IFAC); IFAC Nathaniel B. Nichols Medal (2014).

being taught at several other institutions in the United States, although not as many as I was expecting. That said, some of the topics involved are covered in other courses in nearly every institution that offers a controls specialization. However, given the importance of Kalman filtering, I decided that we needed a dedicated graduate course.

I developed a graduate course on the dynamics and control of MEMS. This course provides a comprehensive overview of MEMS devices and their control systems, including MEMS fabrication processes; sensing and actuation techniques in MEMS; modeling and system identification of MEMS dynamics; and control, signal processing, and interface electronics design for MEMS transducers. We covered a number of case studies (such as MEMS accelerometers, gyroscopes, force sensors, pressure sensors, and nanopositioners) in detail. In addition to learning these topics, students gained hands-on experience with MEMS transducers and real-time controller implementation. The class was divided into groups of four students, each group was assigned a mentor, and each group was given a two degree-of-freedom MEMS nanopositioner to work with. Students then built read-out and drive electronic circuits for their MEMS devices and performed system identification to obtain a model of the system. Each group then designed a two-input, two-output control system to track a zig-zag raster pattern in 2D and implemented the controller in dSPACE in real time. At the conclusion of the course, students produced a six-page report (in the ACC format) that detailed their work. Teaching this course was a lot of fun, and, as you would expect, a lot of work, mainly due to the lab component.

Q. Thank you for your comments.

Reza: Thank you. It's always a pleasure to speak with you, and I would like to use this opportunity to thank you for the service you're providing to our community.

» MEMBER ACTIVITIES *(continued from p. 19)*

a concussion. This particular player was quizzed multiple times during the rest of the conference about basic personal data, such as the names and number of his children, and he begrudgingly gave accurate answers). Another player popped his shoulder out of its socket, which resulted in a visit to the emergency room without further consequences.

We have been assured that there were no lingering effects from these injuries, and we look forward to an injury-free 2019 CDC Cup. The widespread muscle soreness could not be avoided, though; virtually all players suffered from it the day after the game. One could easily spot the game participants among the conference attendees by their varying degrees of limping. However, they all carried their limping as a badge of honor.

In hindsight, there were a number of local arrangements issues that could have been improved upon, such as not waiting to the last second to start planning for the game and recruiting players, ensuring that the field was the proper size, increasing female participation, and bringing a first-aid kit to the game. In spite of these minor hiccups, the inaugural CDC Soccer Cup was a great success—perhaps more socially than athletically—and we look forward to the 2019 iteration in Nice, France!

Jorge Cortes
Magnus Egerstedt
Mihailo R. Jovanovic

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