Feedback Control of the Atomic Force Microscope Micro-cantilever for Improved Imaging

by

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Dedicated to my wife Joanna.

Acknowledgments

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Declaration

The thesis contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. I give consent to the final version of my thesis being made available worldwide when deposited in the Universitys Digital Repository, subject to the provisions of the Copyright Act 1968.

Matthew W. Fairbairn

January, 2013

List of Publications and Awards

During the course of this research a number of papers have been submitted to international journals and conferences. The following is a list of those articles which have been published in international journals or accepted for publication, as well as a list of conference papers which have been presented or accepted for presentation. A number of conference papers were recognized by awards, as indicated.

Journal Articles

1. *Q-Control of an Atomic Force Microscope Micro-cantilever: A Sensor-less Approach*
   M. W. Fairbairn, S. O. R. Moheimani, A. J. Fleming
   IEEE/ASME Journal of Microelectromechanical Systems
   Volume 20, Number 6, page 1372-1381, 2011

2. *Resonant Control of an Atomic Force Microscope Micro-cantilever for Active Q Control*
   M. W. Fairbairn, S. O. R. Moheimani
   Review of Scientific Instruments
   Volume 83, Number 8, page 083708-083717, 2012

3. *A Switched Gain Resonant Controller to Minimize Image Artifacts in Intermittent Contact Mode Atomic Force Microscopy*
   M. W. Fairbairn, S. O. R. Moheimani

IEEE Transactions on Nanotechnology

Volume 11, Number 6, page 1126-1134, 2012

4. *Control Techniques for Increasing the Scan Speed and Minimizing Image Artifacts in Tapping Mode Atomic Force Microscopy*

   M. W. Fairbairn, S. O. R. Moheimani

   IEEE Control Systems Magazine

   Accepted for publication subject to a revision

5. *Sensorless Enhancement of an Atomic Force Microscope Micro-cantilever Quality Factor Using Piezoelectric Shunt Control*

   M. W. Fairbairn, S. O. R. Moheimani

   IEEE Transactions on Nanotechnology

   Accepted for publication. 2013

Conference Proceedings

1. *Passive Piezoelectric Shunt Control of an Atomic Force Microscope Micro-cantilever*

   M. Fairbairn, S. O. R. Moheimani, A. J. Fleming

   Proc. IEEE/ASME International Conference on Advanced Intelligent Mechatronics, page 634–639

   July 3-7, 2011

2. *Improving the Scan Rate and Image Quality in Tapping Mode Atomic Force Microscopy with Piezoelectric Shunt Control*

   M. W. Fairbairn, S. O. R. Moheimani, A. J. Fleming

   Proc. Australian Control Conference, page 26–31

   November 10-11, 2011

3. *Quality Factor Enhancement of an Atomic Force Microscope Micro-cantilever Using Piezoelectric Shunt Control*

M. W. Fairbairn, S. O. R. Moheimani

Proc. IEEE/ASME International Conference on Advanced Intelligent Mechatronics

July 11-14, 2012

4. *Minimizing Probe Loss in Tapping Mode Atomic Force Microscopy Using a Switched Gain Resonant Controller*

   M. W. Fairbairn, S. O. R. Moheimani

   Proc. Australian Control Conference

   November 15-16, 2012

5. *A New Approach to Active Q Control of an Atomic Force Microscope Microcantilever Operating in Tapping Mode*

   M. W. Fairbairn, S. O. R. Moheimani

   Proc. IFAC Symposium on Mechatronic Systems

   April 10-12, 2013

Awards

1. Winner of best student paper award.

   Australian Control Conference. 2011.

2. Winner of best student paper award.

   IEEE/ASME International Conference on Advanced Intelligent Mechatronics. 2012.

3. Best student paper award; high commendation.

   Australian Control Conference. 2012.

4. Best student paper award; finalist.

   IFAC Symposium on Mechatronic Systems. 2013.

Abstract

The Atomic Force Microscope (AFM) is a mechanical microscope capable of producing three-dimensional images of a wide variety of sample surfaces with nanometer precision in air, vacuum, or liquid environments. Tapping mode Atomic Force Microscopy has become a popular mode of operation due to the reduced lateral forces between the probe and sample compared to other modes of AFM operation.

The reliance on feedback control and the complex dynamics associated with this device have made it an interesting topic of research for control systems engineers over the past two and a half decades. Despite the amount of research which has been undertaken to improve the operation of this instrument there is still more room for improvement. The ideas presented in this work provide solutions to several problems associated with imaging in tapping mode with the AFM. These new tools, combined with those of other researchers, are providing scientists with an instrument which can image faster with improved image quality than its predecessors.

When operating an AFM in tapping mode the quality (Q) factor of the cantilever probe places a limitation on scan speed and image quality/resolution. A low Q factor cantilever is required for high scan speeds, whereas a high Q factor cantilever is required for high resolution and to minimize image distortion when scanning soft samples.

One other limitation to scan speed is the ability of the cantilever to track the sample after a large steep downward step in sample topography is encountered. As the

scan speed is increased the likelihood of artifacts appearing in the image is increased due to the probe tip losing contact with the sample.

This work introduces new methods of controlling the Q factor of an AFM micro-cantilever to improve the scan speed and image quality of the AFM operating in tapping mode.

Active Q control, which is based on velocity feedback, is commonly used to modify the effective Q factor of the AFM micro-cantilever to achieve optimal scan speed and image resolution for the imaging environment and sample type. Time delay of the cantilever displacement signal is the most common method of cantilever velocity estimation. Spill-over effects from unmodeled cantilever dynamics may degrade the closed-loop system performance, possibly resulting in system instability, when time delay velocity estimation is used. A resonant controller is proposed in this work as an alternate method of velocity estimation. This new controller has guaranteed closed-loop stability, is easy to tune and may be fitted into existing commercial AFMs with minimal modification. Significant improvements in AFM image quality are demonstrated using this control method.

The feedback signal in the active Q control feedback loop comes from an optical sensor which produces a significant amount of measurement noise. Piezoelectric shunt control is introduced as a new method of controlling the Q factor of a piezoelectric self actuating AFM micro-cantilever. The use of this control technique removes the noisy optical sensor from the Q control feedback loop. The mechanical damping of the micro-cantilever is controlled by placing an electrical impedance in series with the tip oscillation circuit. Like the resonant controller the closed-loop stability of this controller, in the presence of unmodeled cantilever dynamics, is guaranteed. A passive impedance is used to reduce the cantilever Q factor to improve the scan speed when imaging hard sample surfaces in air. An active impedance is used to increase the cantilever Q factor for improved image quality when imaging soft samples, samples with fine features or samples immersed in a fluid. A synthetic impedance was designed to allow easy modification of the control parameters, which may vary with environmental conditions, and to implement the active impedance necessary for cantilever Q factor enhancement.

The switched gain resonant controller is presented as a new method of improving the ability of the cantilever to track the sample when imaging at high speed. The switched gain resonant controller is implemented to switch the cantilever Q factor according to the sample profile during the scan. If the controller detects that the probe tip has lost contact with the sample the cantilever Q factor is increased leading to a faster response of the feedback controller, expediting the resumption of contact. A significant reduction in image artifacts due to probe loss is observed when this control technique is employed at high scan speeds.

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