Field-programmable Gate Array Implementation for High-speed, High-bandwidth Feedforward Control

A half-day (1PM–5PM) workshop at the 2016 American Control Conference, Boston, MA

Organizers and instructors:
Dr. Juan Ren, Department of Mechanical Engineering, Iowa State University
Dr. Qingze Zou, Department of Mechanical and Aerospace Engineering, Rutgers University
Dr. Kam K. Leang, Department of Mechanical Engineering, University of Utah

SUMMARY

Advanced feedforward control techniques have been successfully demonstrated in applications such as high-speed nanopositioning and scanning probe microscopy. In areas such as manufacturing and robotic manipulation, advanced feedforward control is essential to achieve superior performance. Practical implementation of these advanced control techniques in high-speed, high-bandwidth motion control, however, tends to be challenged by hardware limitations, as the conventional microprocessor-based data acquisition systems fail to provide a fast enough round-loop sampling frequency to execute these algorithms. Field-programmable gate array (FPGA) possesses great potential to address this challenge as FPGA does not only provide the hardware flexibility in realizing various controller architectures, but also enable ultra-high round-loop sampling rate to implement advanced control techniques for high-speed, high-bandwidth systems. However, applications of FPGAs by the control community are still rather limited due to factors including unawareness of the advantages of FPGAs or hesitation caused by the technical challenges involved in FPGA-based controller implementations. Therefore, we would like to, through this workshop, bridge the recent advances in advanced control techniques and their implementations in practical applications using FPGA. We will provide a step-by-step tutorial on FPGA for control applications, and stimulate and encourage explorations of advanced feedforward control and FPGA implementations to tackle challenges in emerging areas including biomedical and probe-based microscopy applications. In particular, we will first provide a brief introduction on recent advances in feedforward control techniques, then give a basic tutorial on FPGA and its use in controller design and implementation; second, we will illustrate and demonstrate the applications of FPGA in high-speed motion control using broadband nanomechanical quantification and ultra-high-speed AFM imaging as two examples; and finally, we will conclude the workshop through discussions of the potential and challenges of using FPGAs in emerging applications.

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WORKSHOP OUTLINE

1. Introduction
   (a) High-speed motion control: advanced feedforward control and its applications
      i. Preview-based inversion-based feedforward control
      ii. Optimal and robust inversion
      iii. Inversion-based iterative learning control
   (b) Overview of Field-programmable Gate Arrays (FPGAs)
      i. Implementations of FPGAs for challenging control applications
      ii. Advantages of FPGAs
2. Fundamentals of Implementations of FPGAs
   (a) Technical design and modern development of FPGAs
   (b) Basic architecture of FPGAs: logic blocks, hard blocks, clocking, and 3D architecture
   (c) Basic FPGA algorithm design and programming
3. Applications of FPGAs in High-speed Motion Control
   (a) Controller design using FPGA: implementation, debug and tuning
   (b) Example I: High-speed broadband nanomechanical quantification achieved using FPGA [1, 2]
   (c) Example II: Implementation of high-speed AFM imaging using FPGA [3, 4]
   (d) Example III: Implementation of feedforward hysteresis compensation and integrated high-speed feedback control using FPGA [5, 6]
4. Emerging Applications of FPGAs in Motion Control
   (a) Biomedcial applications—Examples and Challenges
   (b) Video-rate scanning probe microscopy — Examples and Challenges
5. Discussion on Open Problems and Opportunities for Controls Community

[1] J. Ren and Q. Zou, “A control-based approach to accurate nanoindentation quantification in broadband nanomechanical measurement using scanning probe microscope,” *Nanotechnology, IEEE Transactions on*, vol. 13, no. 1, pp. 46–54, 2014.

[2] J. Ren, S. Yu, N. Gao, and Q. Zou, “Indentation quantification for in-liquid nanomechanical measurement of soft material using an atomic force microscope: Rate-dependent elastic modulus of live cells,” *Physical Review E*, vol. 88, no. 5, p. 052711, 2013.

[3] J. Ren and Q. Zou, “High-speed adaptive contact-mode atomic force microscopy imaging with near-minimum-force,” *Review of Scientific Instruments*, vol. 85, no. 7, p. 073706, 2014.

[4] J. Ren, Q. Zou, B. Li, and Z. Lin, “High-speed atomic force microscope imaging: Adaptive multiloop mode,” *Physical Review E*, vol. 90, no. 1, p. 012405, 2014.

[5] Y. Shan and K. K. Leang, “Dual-stage repetitive control with prandtl–ishlinskii hysteresis inversion for piezo-based nanopositioning,” *Mechatronics*, vol. 22, no. 3, pp. 271–281, 2012.

[6] Y. Shan and K. K. Leang, “Design and control for high-speed nanopositioning: serial-kinematic nanopositioners and repetitive control for nanofabrication,” *Control Systems, IEEE*, vol. 33, no. 6, pp. 86–105, 2013.

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TENTATIVE TIMELINE OF THE WORKSHOP

Time	Topic	Speaker
1:00–1:40 PM	Brief tutorial on advanced feedforward control techniques and needs for high-speed online computation	Dr. Qingze Zou
1:45–2:15 PM	FPGA 101 for control applications	Dr. Juan Ren
2:20–3:00 PM	FPGA Control Application Example I: high-speed nanomechanical quantification and high-speed AFM imaging	Dr. Juan Ren
3:05–3:45 PM	FPGA Control Application Example II: implementation of feedforward hysteresis compensation and integrated high-speed feedback control using FPGA	Dr. Kam Leang
3:50–4:30 PM	Emerging applications of FPGAs	Dr. Kam Leang and Dr. Juan Ren
4:30–5:00 PM	Open discussion	

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WORKSHOP ORGANIZERS

Dr. Juan Ren
Assistant Professor
Department of Mechanical Engineering
Iowa State University, Ames, IA 50011 USA
Email: juanren@iastate.edu
Web: http://www.me.iastate.edu/directory/faculty/juan-ren/

Juan Ren is an Assistant Professor in Mechanical Engineering at Iowa State University. She received her B.S. in Process Equipment and Control from Xian Jiaotong University in 2009, and her Ph.D. in Mechanical Engineering from Rutgers, the State University of New Jersey in 2015. Her research interested include nanoscale broadband biomechanics characterization, high-speed imaging and broadband viscoelasticity spectroscopy of soft materials, and system-inversion based feedforward-feedback control theory and implementation to nanotechnology.

Dr. Qingze Zou
Associate Professor
Department of Mechanical and Aerospace Engineering
Rutgers, the State University of New Jersey, Piscataway, NJ 08854 USA
Email: qzzou@rci.rutgers.edu
Web: http://mae.rutgers.edu/content/qingze-zou

Qingze Zou is an Associate Professor in the Mechanical and Aerospace Engineering Department, Rutgers, the State University of New Jersey, USA. He received the bachelor degree in automatic control from the University of Electronic Science and Technology of China, in 1994, the M.S. degree in mechanical engineering from Tsinghua University, Beijing, China, in 1997, and the Ph.D. degree in mechanical engineering from the University of Washington, Seattle, WA, USA, in 2003. Previously he had taught in the Mechanical Engineering Department of Iowa State University. His research interests are in advanced system dynamics and control tools for high-speed scanning probe microscope imaging, probe-based nanomanufacturing, rapid broadband mechanical property measurement and mapping of soft and live biological materials at nanoscale, and micromachining. He received the NSF CAREER award in 2009, and the O. Hugo Schuck Best Paper Award from the American Automatic Control Council (AACC) in 2010. He is a Technical Editor of IEEE/ASME Transactions on Mechatronics (20142017) and past Associate Editor of ASME Journal of Dynamic Systems, Measurement and Control (2011-2014).

Dr. Kam K. Leang
Associate Professor
Department of Mechanical Engineering
University of Utah, Salt Lake City, Utah 84112 USA
Email: kam.k.leang@utah.edu
Web: www.kam.k.leang.com/academics/

Kam Leang is an Associate Professor in the Mechanical Engineering Department at the University of Utah, where he joined in July 2014. Between 2008 and 2014, he was at the University of Nevada, Reno. He received the B.S. and M.S. degrees in Mechanical Engineering from the University of Utah, Salt Lake City, Utah, in December 1997 and 1999, respectively, and the Ph.D. degree from the University of Washington, Seattle, Washington, in December 2004. Dr. Leangs research interests include: modeling and precision control

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of electroactive (smart) material actuators (piezoelectrics and electroactive polymers), nanopositioning and scanning probe microscopy, and more recently design and control of unmanned autonomous systems. His work is supported by the National Science Foundation, U.S. Department of Defense, NASA, and industry partners. He currently serves as an Associate Editor for IEEE Control Systems Magazine and Frontiers in Mechanical Engineering, Nature Publishing.

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