A Full-Day Pre-Congress Workshop for 2017 IFAC World Congress

Iterative Learning Control and Repetitive Control: Theoretical Advances and Emerging Applications

Bing Chu and Chris Freeman, University of Southampton, UK

Tom Oomen, Eindhoven University of Technology, The Netherlands

Kira Barton, University of Michigan, USA

Ying Tan, University of Melbourne, Australia

Workshop Outline

Iterative Learning control (ILC) and repetitive control (RC) are high performance tracking control design methods for systems operating in a periodic or repetitive manner. To achieve this they both adapt the control effort based on information collected from previous trials (periods). Compared to conventional control design approaches, ILC and RC potentially lead to significantly better performance even without accurate system model information. Originating from robotic research, ILC and RC have attracted intensive research effort and have proven to be extremely successful in achieving attractive system performance in a wide range of application domains, including manufacturing processes, mechanical testing equipment, chemical batch processes and next generation health care.

After more than 30 years, ILC and RC have progressed considerably in both theoretical research and its practical application. This workshop, together with an open invited track within the main conference, aims to provide an overview of the latest advances in ILC and RC and to create a forum for high quality discussion of both theoretical and practical perspectives. In particular, the workshop aims to:

- Bring together results representing the dominant analysis and design paradigms, including internal model design, norm-optimal design, frequency domain design, and design for nonlinear systems

- Address new theoretical challenges in ILC and RC, including robustness and flexibility to varying tasks, networked systems, etc.

- Present new emerging and non-traditional applications

- Discuss future challenges and opportunities in ILC and RC

The workshop also features a poster session providing a great opportunity for the participants to showcase their work both to the ILC/RC community and to the broad audience.

A webpage of the work shop can be found at https://goo.gl/v82ELH

Desired Learning Outcomes

By the end of the workshop, the audience will be able to:

- Identify (traditional and emerging) applications of ILC and RC

- Design ILC and RC using state of the art methodologies

- Develop knowledge of future research challenges and opportunities in ILC and RC

Intended Audience and Desired Prerequisite

We expect the audience to include academics, postgraduate students as well as industrial researchers and engineers with an interest in ILC and RC. Prerequisite knowledge in this area is not necessary as this will be covered in the workshop. In recent years, the workshop proposers have organized ILC invited sessions at the American Control Conference (annually since 2009, excluding 2012), as well as at the 2015 CDC. Historically, these sessions have been well attended with 35-40 people in attendance on average and a balanced participation from North America, Europe, and Asia. The proposed IFAC workshop promises to have broad appeal as well.

Workshop Schedule

- **Opening**
  - 0900-0910: Introduction and Motivation
- **Session #1: Tutorial and state of the art (I)**
  - 0910-0955: An Introduction to Repetitive Control, Iterative Learning Control and Discrete Repetitive Processes: Historical and Future Perspectives (Kevin Moore)
  - 0955-1040: Iterative Learning Control: An Optimization Paradigm (David Owens)
- *break 10:40 – 11:00*
- **Session #2: Tutorial and state of the art (II)**
  - 1100-1145: Frequency Domain ILC: Design Aspects, Flexibility to Varying Tasks, and Multivariable Systems (Tom Oomen)
  - 1145-1230: Iterative Learning Control for Nonlinear Systems Satisfying Local Lipschitz Continuity Condition (Ying Tan)
- *Lunch 1230-1330*
- **Session #3: Emerging topics and applications (I)**
  - 1330-1400: Spatial ILC for Applications in Additive Manufacturing (Kira Barton)
  - 1400-1430: ILC for Spatial Trajectory Tracking (Bing Chu)
  - 1430-1500: Next Generation Assistive and Rehabilitation Technology - the Challenges for ILC and RC (Chris Freeman)
- *poster session & break 1500-1545*
- **Session #4: Emerging topics and applications (II)**
  - 1545-1615: ILC of Microfluidics (Deqing Huang)
  - 1615-1700: ILC from An Industrial Perspective (Mikael Norrlöf)
- **Open Discussion – Challenges and Opportunities 1700-1730**
- **Closing**
  - 1730: Concluding remarks

Workshop Speakers

1. Professor Kevin L. Moore, Colorado School of Mines, USA

Biography: Professor Kevin L. Moore is the Dean of the College of Engineering and Computational Sciences at the Colorado School of Mines. He received the B.S. and M.S. degrees in electrical engineering from Louisiana State University and the University of Southern California, respectively. He received the Ph.D. in electrical engineering, with an emphasis in control theory, from Texas A&M University in 1989. He has been an Assistant and Associate Professor at Idaho State University (1989-1998); an Associate and Full Professor of Electrical and Computer Engineering at Utah State University, where he was the Director of the Center for Self-Organizing and Intelligent Systems, directing multi-disciplinary research teams of students and professionals developing a variety of autonomous robots for government and commercial applications (1998-2004); a senior scientist at Johns Hopkins University's Applied Physics Laboratory during a one-year research stay, where he worked in the area of unattended air vehicles, cooperative control, and autonomous systems (2004-2005); and a Full Professor of Engineering at the Colorado School of Mines (2005-present), where he was Director of the Center for Robotics, Automation, and Distributed Intelligence and the G.A. Dobelman Distinguished Professor (2005-2011). He also worked in industry for three years pre-Ph.D as a member of the technical staff at Hughes Aircraft Company. His research interests include iterative learning control, autonomous systems and robotics, and applications of control to industrial and mechatronic systems, including the cooperative control of networked systems. He is the author of the research monograph Iterative Learning Control for Deterministic Systems, co-author of the book Sensing, Modeling, and Control of Gas Metal Arc Welding, and co-author

of the research monograph Iterative Learning Control: Robustness and Monotonic Convergence for Interval Systems. He is a licensed professional engineer, involved in several professional societies and editorial activities, and is interested in engineering education pedagogy, particularly capstone senior design. He is an ABET Program Evaluator, a senior member of IEEE, a member and past chair of the IEEE Control System Society Technical Committee on Intelligent Control, and has served on several editorial boards.

2. Professor David H. Owens, Zhengzhou University, China and University of Sheffield, UK

Biography: Professor David H. Owens has 47 years of experience of Control Engineering theory and applications in areas including nuclear power, robotics and mechanical test. His research has included multivariable frequency domain theory and design, the theory of multivariable root loci, contributions to robust control theory, theoretical methods for controller design based on plant step data and involvement in aspects of adaptive control, model reduction and optimization-based design. His early experience of modelling and analysis of systems with repetitive dynamics originally arising in control of underground coal cutters led to substantial contributions (with collaborator E. Rogers and others) in the area of repetitive control systems (as part of 2D systems theory) but more specifically, since 1996, in the area of iterative learning control when he introduced the use of optimization to the ILC community in the form of "norm optimal iterative learning control". Since that time he has added considerable detail and depth to the approach and introducing the ideas of parameter optimal iterative learning to simplify the implementations. This led to his development of a wide range of new algorithms, many of which are introduced in his recent Springer text "Iterative Learning Control: an optimization paradigm". Applications have included industrial projects in automotive/mechanical test and the development of data analysis tools for control of gantry robots and stroke rehabilitation equipment with collaborators at Southampton University. David Owens was elected a Fellow of the UK Royal Academy of Engineering for his contributions to knowledge in these and other areas.

3. Dr Tom Oomen, Eindhoven University of Technology, The Netherlands

Biography: Tom Oomen received the M.Sc. degree (cum laude) and Ph.D. degree from the Eindhoven University of Technology, Eindhoven, The Netherlands. He held visiting positions at KTH, Stockholm, Sweden, and at The University of Newcastle, Australia. Presently, he is an assistant professor with the Department of Mechanical Engineering at the Eindhoven University of Technology. He is a recipient of the Corus Young Talent Graduation Award and the 2015 IEEE Transactions on Control Systems Technology Outstanding Paper Award. He is Associate Editor on the IEEE Conference Editorial Board and IFAC Mechatronics. His research interests are in the field of system identification, robust control, and learning control, with applications in mechatronic systems.

4. Dr Ying Tan, University of Melbourne, Australia

Biography: Dr Ying Tan is an Associate Professor and Reader in the Department of Electrical and Electronic Engineering at The University of Melbourne. She received her Bachelor's degree from Tianjin University, China, in 1995, and her PhD from the National University of Singapore in 2002. She joined McMaster University in 2002 as a postdoctoral fellow in the Department of Chemical Engineering. She joined the Department of Electrical and Electronic Engineering Department at the University of Melbourne in 2004. Her main areas of research are nonlinear systems, on-line optimization and intelligent control systems. She has published 110 papers in journals and conferences and has attracted more than 2 million Australian dollars in research funding. She currently is Associate Editor for Systems and Control Letters, Asian Journal of Control. She is the steering committee member for Asian Control Association and Co-Chairs for Asian Control Conference 2017. She was awarded an Australian Postdoctoral Fellow (2006-2008) and a Future Fellow (2009-2013) by the Australian Research Council. She was the one of finalists for Best Student Paper Award, American Control Conference.

5. Professor Kira Barton, University of Michigan, USA

Biography: Professor Kira Barton received her B.S. degree in Mechanical Engineering from the University of Colorado at Boulder in 2001. Barton continued her education in mechanical

engineering at the University of Illinois at Urbana-Champaign and completed her M.S. and Ph.D. degrees in 2006 and 2010, respectively. She held a postdoctoral research position at the University of Illinois from Fall 2010 until Fall 2011, at which point she joined the Mechanical Engineering Department at the University of Michigan at Ann Arbor. Her primary research focus is on precision coordination and motion control for emerging applications, with a specialization in iterative learning control. Barton's work intersects controls and manufacturing and combines innovative manufacturing processes with enhanced engineering capabilities. The potential impact of this research ranges from building high-resolution DNA sensors for biological applications, to the integration of advanced sensing and control for rehabilitation robotics.

6. Dr Bing Chu, University of Southampton, UK

Biography: Dr Bing Chu is a lecturer in Electronics and Computer Science at University of Southampton, UK. Before joining University of Southampton in 2012, he was a postdoctoral researcher at University of Oxford (2010-2012). He obtained his BEng degree in Automation and MSc degree in Control Science and Technology from Tsinghua University, Beijing, China in 2004 and 2007, respectively. In 2009, he completed a PhD degree in Automatic Control and Systems Engineering from the University of Sheffield, UK. He has been the recipient of a number of awards including the best paper prize 2012 UKACC and Certificate of Merit for 2010 IET Control and Automation Doctoral Dissertation Prize. His current research interests include iterative learning and repetitive control, analysis and control of large scale networked systems, applied optimisation theory, and their applications to robotics, power electronics and next generation healthcare.

7. Dr Chris Freeman, University of Southampton, UK

Biography: Dr Chris Freeman is a Reader in applied control within Electronics and Computer Science (ECS) at the University of Southampton. He received the B.Sc. degree in mathematics from the Open University, the B.Eng. degree in electromechanical engineering from the University of Southampton, and the Ph.D. degree in control systems from the same institution. His control research interests include iterative learning and repetitive control theory and their experimental application to industrial systems and biomedical engineering. He has led the engineering component on large UK government funded grants that have developed a range of upper limb rehabilitation systems using robotic and Functional Electrical Stimulation (FES) technology that have each been trialled clinically with stroke patients. In this area his current focus is on biomechanics, motor learning and control, non-contact sensing, electrode-array based FES, and wearable technology.

8. Professor Deqing Huang, Southwest Jiaotong Univeristy, China

Biography: Dr Deqing Huang received the B.S. and Ph.D. degrees with a major of applied mathematics from the Mathematical College, Sichuan University, Chengdu, China, in 2002 and 2007, respectively. He attended the Department of Electrical and Computer Engineering (ECE), National University of Singapore (NUS), Singapore, in 2006, where he received the second Ph.D. degree with a major in control engineering in 2011. From January 2010 to February 2013, he was a Research Fellow in the Department of Electrical and Computer Engineering of NUS. From March 2013 to January 2016, he was a Research Associate with the Department of Aeronautics, Imperial College London, London, U.K. In January 2016, he joined the Department of Electronic and Information Engineering, Southwest Jiaotong University, Chengdu, China as professor and department head. He is the member of the IEEE and the member of IEEE Industrial Electronics Society. His research interests lie in the areas of modern control theory, fluid system analysis and control, convex optimization, and robotics.

9. Professor Mikael Norrlöf, Linköping University, Sweden

Biography: Adjunct Professor Mikael Norrlöf got his PhD in 2000, docent in 2005 and became adjunct professor in 2009, all at the Dept of EE., Linköping University, Linköping, Sweden. From 2007 he is at ABB Robotics, Västerås, Sweden, where he currently act as Senior Principal Engineer and in the role motion control architect. He is also robotics area responsible in the Industrial Excellence Center LINK-SIC at Linköping University. His main research interest is in industrial robotics and the main contribution of his research is in Iterative Learning Control where

he has developed theories and also contributed with experiments on different industrial robot platforms, and also been involved in the product development at ABB. He is also working and contributing in areas such as path and trajectory planning, sensor fusion, and diagnosis, with applications in robotics.